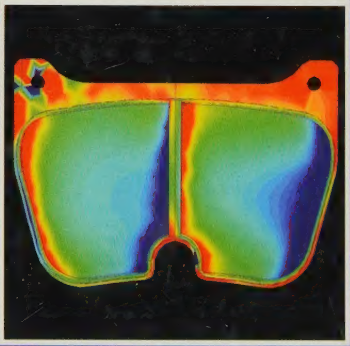
AUTOMOTIVE DISC BRAKE MANUAL

Haynes

3542

The complete guide to the theory and practice of automotive disc braking systems



- From metallurgy to routine maintenance
- Faults illustrated and explained
- Full colour throughout

TECHBOOK

Automotive Disc Brake Manual

Produced in collaboration with Brembo SpA

The complete guide to the theory and practice of automotive disc braking systems **(3542 - 128)**

A book in the Haynes Techbook Series

ABCDE
FGHIJ
KLMNO
PQRST
1 2 3

ISBN **1 85960 542 7**

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Haynes Publishing
Sparkford Nr Yeovil, Somerset BA22 7JJ, England

Haynes North America, Inc.
861 Lawrence Drive, Newbury Park, California 91320, USA

Editions Haynes S.A.
Tour Aurore - La Défense 2, 18 Place des Reflets,
92975 PARIS LA DEFENSE Cedex, France

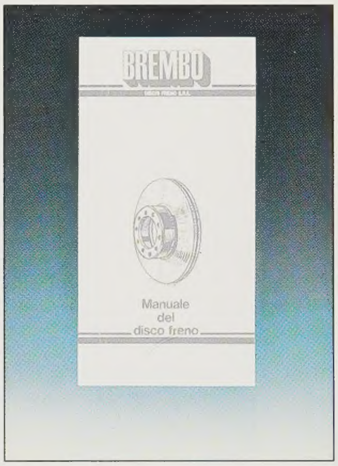
Haynes Publishing Nordiska AB
Box 1504, 751 45 Uppsala, Sverige

Preface

Curno, September 15 1997

Brembo published its first Brake Disc Manual in June 1985. This was a twenty page volume that highlighted the disc's role in "disc" braking systems (quite often misunderstood) and gave indications on necessary checks and maintenance of the disc, whilst emphasising the skills required to manufacture a component capable of offering guarantees of efficiency, safety and durability.

Today it is even more true to say that the brake disc remains a little-known, although vital, component. The rules of the game have changed. Asbestos has been eliminated from brake pad composition and vehicles are now heavier. For instance, an unladen 1974 Golf 1.5 weighed 780 kg whereas the Golf 3, 1.4 weighs 1030 kg. Even so it is still equipped with the same 239 x 12 mm Brembo brake disc, code 08.4177.10. This fact in itself has proved to be non-critical as far as this vehicle is concerned. Similar developments for other cars, however, have led to the exceeding of a brake discs limits. It is important to understand why. This is one of the aspects that this Manual aims to clarify. Today, cars are faster and make less noise. Users are now much more demanding and less willing to tolerate noises and vibrations that, in the past, were lost in the background noise but which today can often be heard and are rarely accepted.



I felt that Brembo should update the earlier volume and make the new manual a tool that explains the principles and developments of disc brake systems in general and the brake disc in particular: how does it function, why and how does wear occur, how can correct vehicle maintenance be ensured?

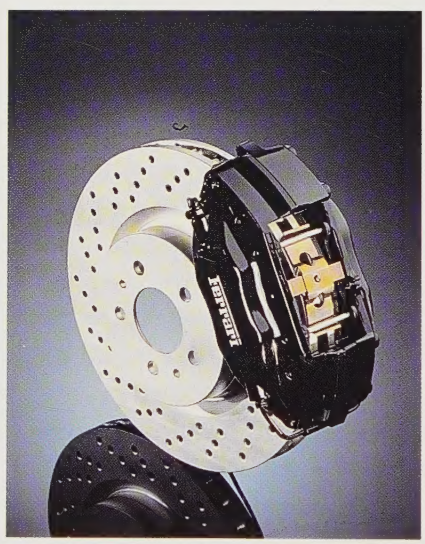
It is a fact that competently fitted Brembo brake discs give all cars the assurance of high performance, safety and comfort for a long time to come.elevate, sicurezza e comfort.

Alberto BOMBASSEI

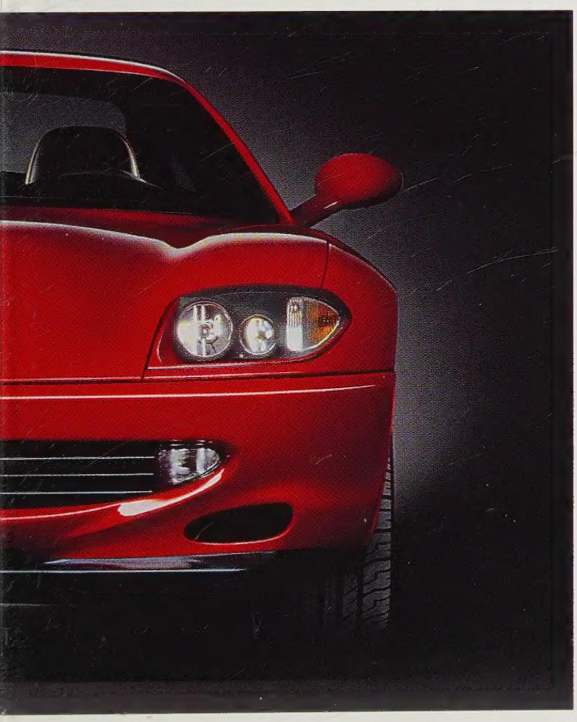
President

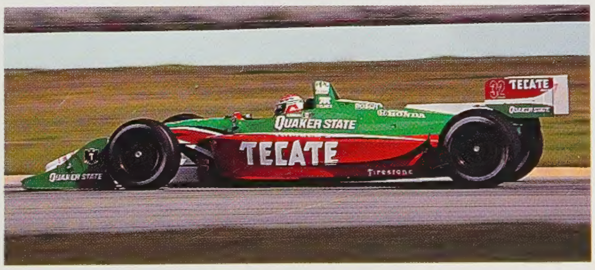
BREMBO: DISCOVERING A UNIQUE REALITY IN THE FIELD OF BRAKING SYSTEM TECHNOLOGY

Think of the car you have been dreaming about recently: consider that, whatever it looks like, there are high probabilities that the brakes for it are purpose designed, engineered and produced by Brembo. Surprised! Go on reading and you will discover more about the state-of-the-art braking systems we provide for the vehicle industry.
Given our unique capabilities for understanding and developing brake caliper and brake disc technology, Brembo is the natural choice for the most demanding applications for top of the range sports cars and luxury saloons. Our expertise even includes the complete wheel-end module, granting an unrivalled level of performance to the most beautiful cars produced in Japan, U.S.A. and Europe today.
Back in the early seventies, Brembo pioneered disc brake technology for motorcycles. Today we supply the Euro-

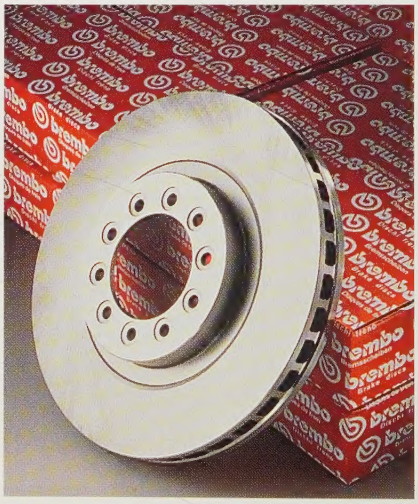


pean industry with best-in-class braking systems that inherit continuous improvements from our racing experience.
Not surprisingly, our logo is also proudly shown by some Japanese flagships produced in Japan or abroad. Along with this, the best-selling scooters are today equipped with Brembo braking systems. To our customers this means added value to their bikes; to you it means top performance and driving safety.
In recent years a dramatic technical change has been affecting the truck market, with all the newly released platforms having disc braking systems replacing the old drum brake design. You can easily guess, Brembo was there, prepared to offer all of its experience to a brand new segment. We therefore established firm leadership in the design and manufacture of brake discs for these vehicles, as well as a supremacy in hydraulic brake calipers for light and medium trucks.





Over the years we have developed and produced in excess of 900 different designs of brake discs. Nobody else in the world has such wide knowledge available. Today, the Brembo range of discs and drums is the most complete you can choose from for your replacement parts, and each item comes to you quickly and with the guarantee, that only Brembo can deliver, that all the discs are manufactured under the most stringent quality parameters in our plants in Europe and North America. When you look for the very best in replacement brake discs and drums for your car Brembo is the right word. That is why we are the largest worldwide producer of these essential tools for your active safety.



Gold is the metal that drivers using our brakes in the racing arena are tasting more often. We helped them win more than 120 world championships in the various car and motorbike categories since we entered racing in 1975. Brembo has today a firm leadership in this segment and our products are on most F1, Indy, NASCAR, Rally teams, as well as on virtually all of the top motorcycle teams.

The experience we gain from these testers is usually passed to the road products.
Second place is worth nothing in the hot climate we enjoy every weekend. That is why Brembo is the preferred choice for this breathtaking goldrush.
What you should expect from the most dynamic player in the very competitive scenario of today's braking industry is continuous innovation made available to the everyday driver. This is exactly our commitment, thanks to a new breed of products that will be equipping the best cars and motorcycles you will see around over the next few months and years. Looking further ahead, wire technology brakes and brakes made of reinforced and composite materials which are being tested in our laboratories today will become standard one day on cars that may well be driven with a joystick!
If you just came across Brembo today, you are welcome into a world apart, the best in braking and allows you to enjoy superior pleasure and safety in your everyday driving.

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Chapter 3

Braking System Maintenance

Chapter 4

Causes and consequences of disc deterioration: practical examples

1.1

1.1. A SHORT HISTORY

It goes without saying that if the wheel had not been invented then none of our current means of transport would exist. What we know less about is the date of this invention. Historians believe that it occurred between 5000 and 4000 years ago and, moreover, that the first wheel was not used for transport purposes but to construct rudimentary tools. One of the earliest applications was probably the potter's wheel, a device which made it easier to create vessels for collecting and heating water. This device was then improved when artisans of the day added a second wheel. The first wheel, the upper one, was clearly where clay was placed and modelled as it rotated, while the lower wheel on the same axis was the "engine" that the potter caused to rotate by using his feet. When the artisan wanted to stop the wheel or simply slow it down, he braked it by pressing the underside of his foot against the lower wheel. The birth of the first brake disc. A long time passed before vehicles - those drawn only by animals - were equipped with true brakes. Various systems were fitted to cabs and stagecoaches in order to slow them down: pole lever brakes, band brakes and then brakes with a wooden shoe that rubbed against the wheel tread. This type of brake is still used today in agriculture. The first cars had an even greater disadvantage; they had no brakes at all. This was true of the first steam-driven wheeled vehicle developed by Nicolas CUGNOT in 1769. Testing was brought to a halt when the vehicle collided with a wall because of the lack of brakes.

The potter, first user of a disc brake.

Scholars of the day did not wait for the development of efficient brakes before formulating the laws of friction, laws still used today by brake engineers. Men such as AMONTONS in the 17th century and COULOMB one century later. The science in question is known as tribology.

The original application of braking relative to means of locomotion was for mining skips, then later it benefited by the development of railways. Pioneers in this field were George and Robert STEPHENSON, followed by George WESTINGHOUSE. The latter performed rigorous experiments that overcame prejudice existing at the time and enabled him to formulate the following laws:

- friction coefficient varies with speed;
- friction coefficient diminishes with the application of pressure (fading effect);
- braking is more efficient when the wheels are turning as opposed to when they are blocked. Today's ABS is an application of this law.

But it was only with the advent of petroleum and its use as a fuel in combustion engines that true car brakes were developed. In effect there was an increase in speed, safety was reduced and accidents multiplied.

At around the same time (from 1895 to 1900), Karl BENZ, F.W. LANCHESTER, Al-

Cugnot's Fardier (1769). First self-moving vehicle.
Photo Turin Car Museum

bert de DION and Georges BOUTON developed and marketed the first cars. It was LANCHESTER, however, who applied for a patent for the disc brake in 1902. This consisted of a thin metal disc fixed to the wheel axle that was gripped when braking by two friction material parts, operated by means of levers and rods. Results were quite disappointing because of the lack of suitable materials and the inefficiency of the control circuit.

During the same period Herbert FROOD (Ferodo) made significant progress in terms of brake technology and safety when he developed and patented the first modern friction materials.

In 1922 Malcolm LOUGHEAD (Lockheed) substituted mechanical transmission by a hydraulic transmission system.

1.1 One of the major steps forward in disc brake development happened in 1953 when DUNLOP equipped a Jaguar XK 120 with disc brakes. This car driven by ROLT de HAMILTON won the Le Mans 24-hour race. One year later in 1954 ventilated discs made their first appearance on an Alfa Romeo.
However, it was not until 1963 that an heavy truck was equipped with a Knorr

DUNLOP caliper (1953). BREMBO Archives.

disc brakes while the technology was first applied to production line motorbikes in 1969.

1.2 DISC BRAKES

A brake is any type of system that slows down and halts a vehicle's forward progress, but also the rotation or movement of a body in motion. When a system only slows down speed but is unable to bring a body to a complete halt (as, for instance, in constant deceleration) it is more correct to use the term deceleration. Cases in point are the engine brake and electrical decelerators.
Vehicle brakes have evolved as a result of two different, but simultaneous, trends: on the one hand, technology has become increasingly more complex as a result of modern calculation and production techniques; on the other, the principle and mechanics, in the physical sense of the term, have become simpler.
The best example of this can be found in a comparison of the drum brake to the disc brake.
Drum brakes are relatively simple to manufacture: a casted and machined drum, mechanically welded brake shoes to which the lining is bonded, a mechanical or hydraulic actuator plus a few springs. The mechanics underlying these brakes is, however, very complex and it is therefore rather difficult to predict and analyse their behaviour. As we will see later, the disc brake requires much higher precision during the production stage although its mechanical behaviour is much easier to analyse.

1.2.1 VEHICLE BRAKING

A vehicle in motion cannot be considered a permanent energy conversion system. Two conversions take place in the engine: from chemical energy to thermal energy (fuel combustion), followed by conversion of a part of this thermal energy into mechanical energy (compression, expansion of combustion gases and piston movement). This mechanical energy is transmitted to the vehicle in the form of kinetic or potential energy. Under stable conditions, namely at a constant speed and on a flat surface, the energy produced by the engine is entirely converted into heat as a result of numerous instances of friction: air resistance against the bodywork, friction of moving parts and that of the tyres against the ground. When braking, the vehicle's kinetic energy is entirely converted into thermal energy by the interaction of the brake pads and discs. In our example, the vehicle's kinetic energy is equal to 666 kJ. When the vehicle comes to a complete halt all of this energy is found in the form of heat in the

example:

$$E_{cin} = \frac{1}{2} M\, v^2$$

M = vehicle mass = 1200 kg
v = speed of movement
= 120 km/h = 33.33 m/s
E_{cin} = Kinetic translation energy
= 666.533 Joule = 159 kcal

1.2.1 brakes. By way of example, this thermal energy would be sufficient to bring a little more than 2 litres of water at ambient temperature to the boil.

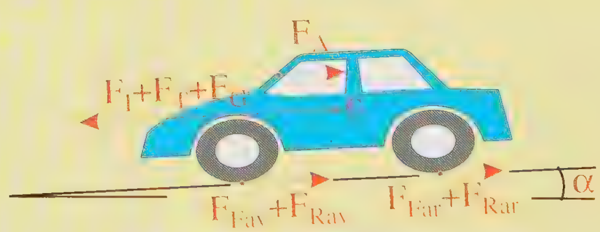
The vehicle in motion is also subjected to a series of forces, the result of which causes either acceleration or deceleration.
Aerodynamic resistance is the result of air friction against the bodywork; it depends on the shape and size of the vehicle (**S**urface and $\mathbf{C_x}$) and increases with the square of the speed.

$$F_A = \frac{1}{2}\rho \; S\, C_x\, v^2$$

ρ is the density of air

Tractive effort FT is provided by the engine and is zero when the clutch is engaged. When acceleration ceases it becomes negative: this is the engine brake.
Force of gravity accelerates or brakes the vehicle according to whether the latter is going down or up an incline. In this case it is the potential energy applied to the mass of the vehicle that decreases or increases. α is the incline of the road (the example shows a 5% downward slope).
Wheel slip resistance is the result of tyre friction against the ground. This force depends on the speed, tyre pressure, weight of the vehicle and, naturally, road

In our example



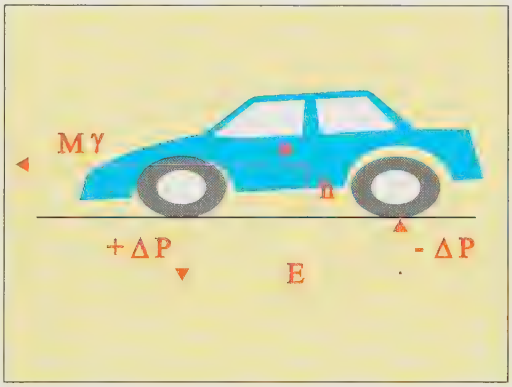
$$F_A + F_T + F_G + F_R + F_F + F_I = 0$$

FA = aerodynamic resistance = 322.4 Newton
FT = traction force = 0 (engine with clutch disengaged)
FG = force of gravity = Mg sin (α) = 588.6 Newton
FR = movement resistance = FR front + FR rear = 18 N
FF = braking force = FF front + FF rear = 5048.2 Newton
FI = force of inertia = M.γ = - 4800 Newton
The braking distance will be 138.8 metres and will require 8.33 seconds.

1.2.1

conditions. It is generally weak except in cases of travelling at high speed with low tyre pressure.
During braking front and rear **braking forces** are exerted at the wheel/ground interface. Their characteristics will be described in detail later. Except in cases of very steep uphill slopes, these are the main forces counteracting the vehicle's forward motion.
Force of inertia is the outcome of all the positive and negative forces applied to the mass of the vehicle. It determines acceleration or deceleration γ (in this case equal to -4m/s2, namely deceleration, in as much as the result is negative).

When at a standstill the weight of the vehicle is borne by the wheels, that is to say, on the front and rear axles. Distribution of the mass depends on where the centre of gravity is located and, therefore, on the position of the load and passengers. In the acceleration or deceleration phase the vehicle is subject to stresses from a number of forces which, however, are not all exerted at the same point. We can state that the force of inertia acts at the centre of gravity while the braking forces act at the wheel/ground interface. During braking these various forces tend to make the vehicle rock, for instance in a forward direction. The weight borne by each wheel is then modified by **load transfer** from the rear to the front section.



Load transfer during braking.

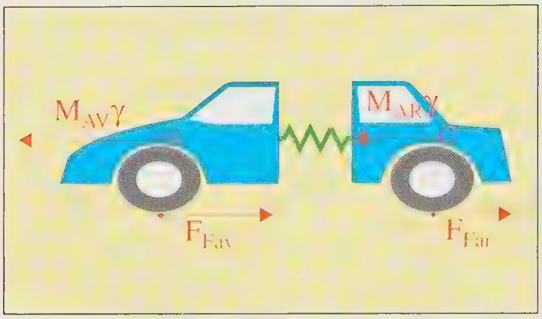
$$\Delta P = M\gamma\frac{h}{E}$$

This value is given by the height of the centre of gravity and the wheelbase (the distance between the two axles).
The load borne by the wheels can reach variations between 10% and 30% when compared to static load distribution. Consequently this factor must be taken into account in designing a braking system.

As a result of all these variables the braking force acting on the front axle is not equal to that acting on the rear axle. The same can be said for forces acting during acceleration. It is possible to hypothesise their exact respective values in a case where the intention is to maintain the vehicle in perfect equilibrium. This equilibrium can be represented by the **equal distribution curve**. If we were to imagine a vehicle that is cut in half and where the two parts are simply con-

1.2.1

Distribution of braking forces.



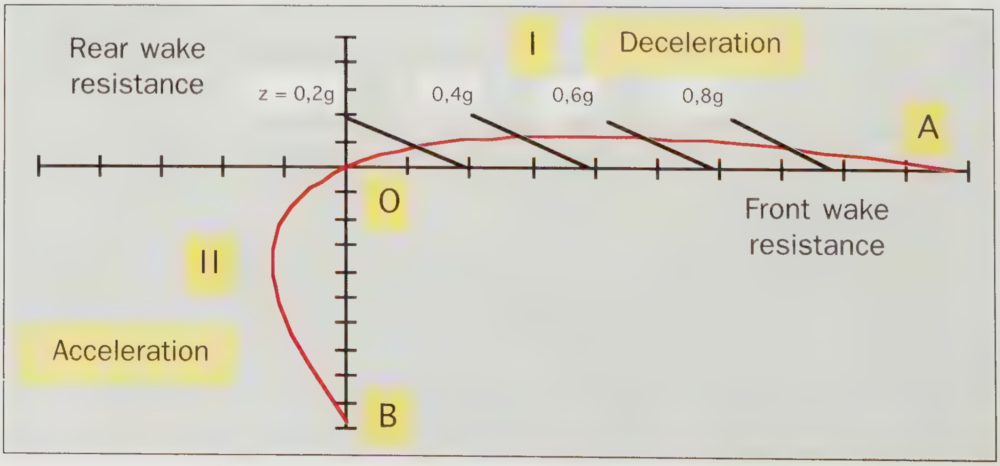
nected by a spring, we could state that there is equal distribution when the spring is neither stretched nor compressed. This is in fact the case when accelerations are identical. Furthermore, we should not forget that both the front and rear mass varies with load transfer. Part I of the curve represents braking whereas part II represents four-wheel drive traction, which is not necessarily always the case as far as cars are concerned.

At point A front braking action is very strong whereas it is almost zero at the rear and as a result the vehicle dips at the front and the rear wheels lift. At point B, rear traction is so strong that in this case the front wheels lift.

Here we are interested in part I of the curve and, of this, only that section which is effectively utilised. Further information can be added to this area of the graph, first and foremost, a set of parallel lines representing the constant deceleration values. In the graph values have been restricted to 0.8g since few cars (and few tyres) can reach or exceed this value.

We know that braking action depends to a large extent on tyre grip. Naturally this is better on a dry as opposed to a wet surface; however, by increasing the intensity of braking action the moment always arrives when the wheel locks. The straight line on the graph indicates the different conditions under which wheels on one axle will lock. This line runs from a point at which only the axle in question brakes while the other does not brake at all, to another point where the axle locks because it serves no purpose, in as much as the other axle alone provides the braking action. That part of the graph representing no locking falls between two straight lines: one for the front and one for the rear axle.

Distribution curve.

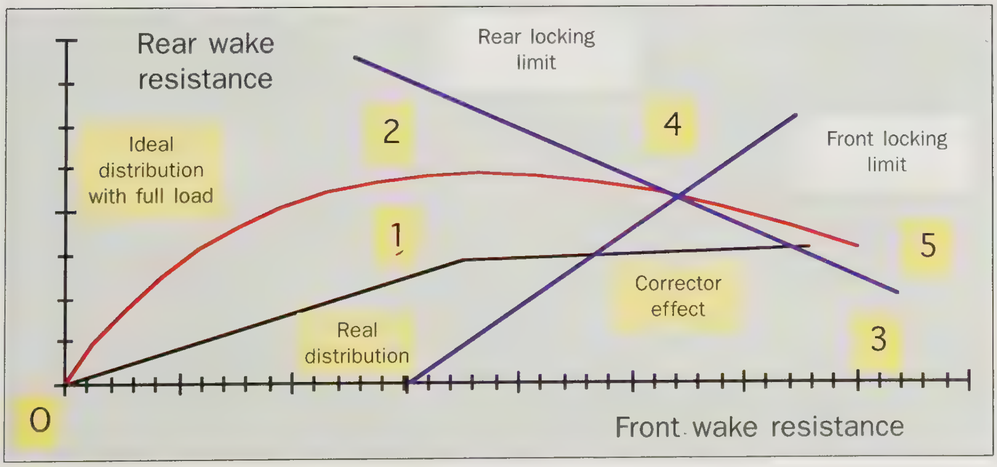


The curve and these two straight lines indicate five areas:
- **1** is the front-dominated area,
- **2** is the rear-dominated area,
- **3** is the front locking area,
- **4** is the rear locking area,
- **5** is the area where both axles lock.

When the vehicle is in motion, wheels do not rotate at the same speed as the vehicle's speed relative to the road. During acceleration they rotate faster while in braking they rotate slower: this is **slip**. In the latter case it can be demonstrated that if slip increases excessively and eventually reaches locking point, transverse stability is seriously compromised. When car manufacturers calculate the braking system, they always define it to function in **area 1**. The equal distribution curve depends on the vehicle, not on the braking system. On the other hand the real distribution curve depends on the load and its distribution and so it varies on the basis of the use made of the vehicle. This is why the real curve for the braking system is always determined as far as possible to tend towards the theoretical curve (equal distribution), even though it always remains below this. In order to better regulate distribution, manufacturers equip the braking circuit with correctors that, depending on the situation, modify the following relationship:

$$\frac{\textbf{Increased front pressure}}{\textbf{Increased rear pressure}}$$

In spite of this there can be certain situations where the wheels lock, for instance, when the road surface is very slippery. The result is directional instability. The intention of the **anti-lock systems** fitted on today's cars is to correct this problem in as much as it seriously compromises safety. The principle in itself is simple though it is difficult to implement; it consists in temporarily diminishing braking

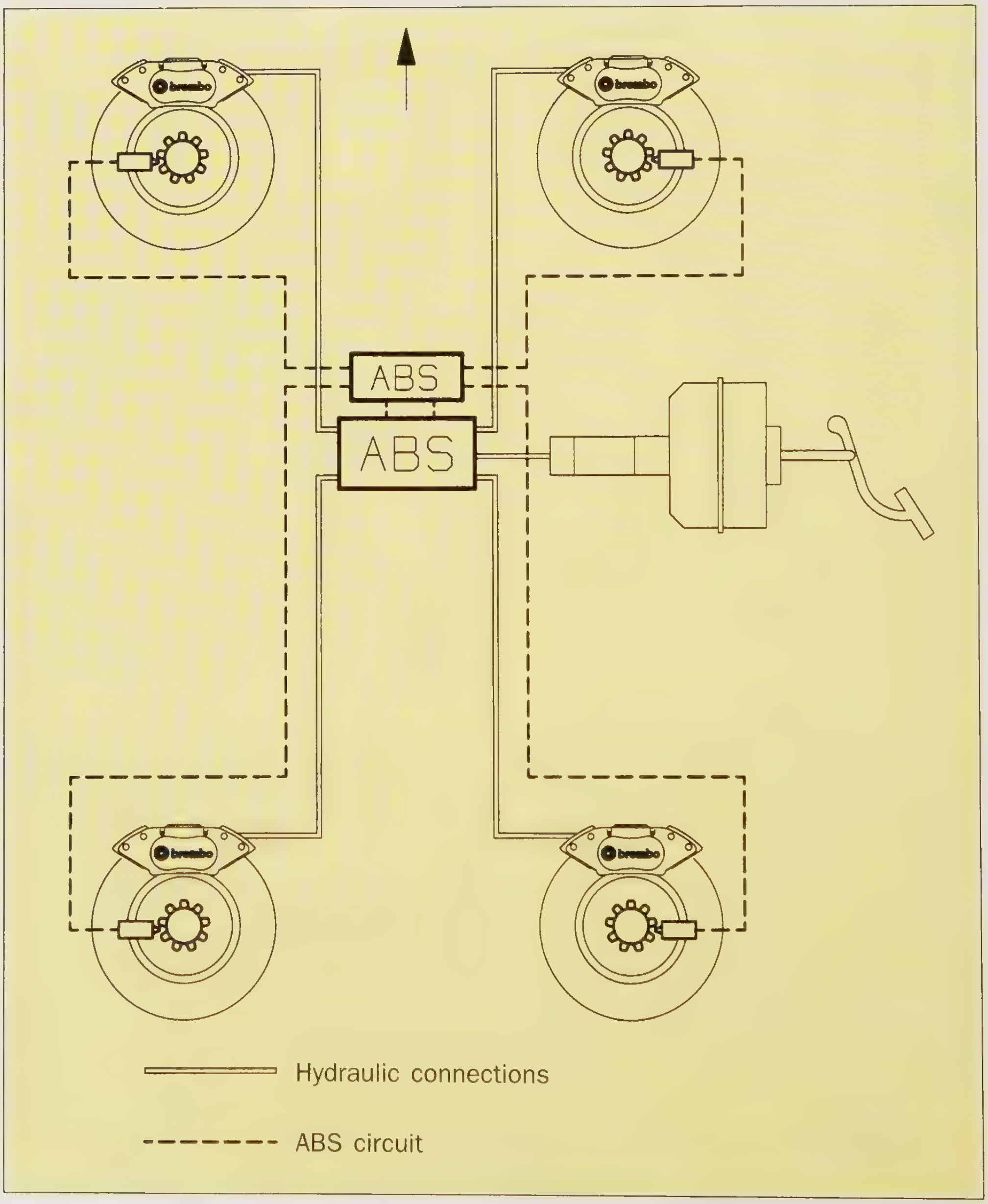


Distribution curve (part 1).

1.2.1

effort on the locked wheel so that it can start to rotate again and find stability. In effect braking performance is somewhat impaired, but the advantage is that safety is re-established.

Principle of ABS.

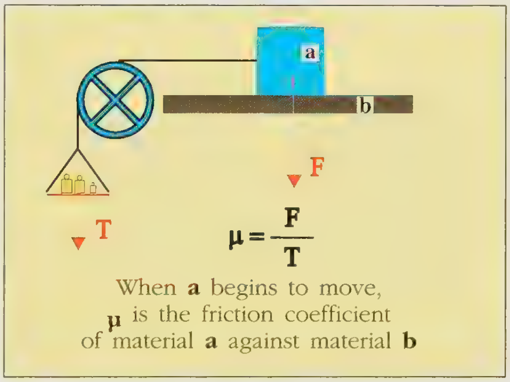


1.2.2

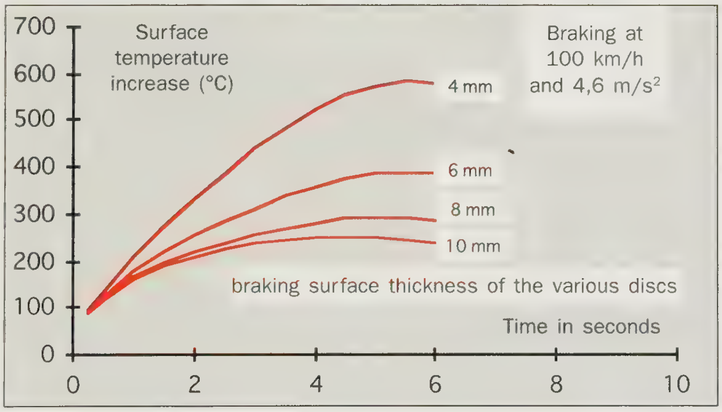
1.2.2 FRICTION MECHANISMS

Whether it is tyre grip or efficiency of brake pads that tend to reduce disc and therefore vehicle speed, the basic mechanism that comes into play is always **friction**. The branch of physics that studies friction is known as **Tribology**. Regarding this science, that analyses the principles underlying interaction between two materials in motion and the wear deriving from this, we will mention only the notion of **friction coefficient**, normally denoted by the letter μ. In the case of brake pad-disc contact its value is less than 1 and in the majority of cases around 0.4, whereas the tyre to ground coefficient is 0.8.

Friction is the basic mechanism whereby mechanical energy is converted into thermal energy. Production of heat is related to breakages that occur when the materials come into contact. This can be the breakage of crystals due to **abrasion**: the rubbing action of very hard particles breaks up the material that is opposed to it. The other mechanism is known as **adhesion-breakage**: pressure and temperature cause the diffusion of one material within the other or even the fusion of one of the materials. Since the two elements move in opposite directions, the bonding breaks up, releasing heat. Both of these mechanisms come into play when a pad makes contact with the disc. It is mainly the disc's cast iron that melts as, in fact, the temperature in the first microns under the surface can reach and exceed the melting point of cast iron. This is an extremely difficult phenomenon to measure. One possible method is to position thermocouples a few millimetres below the surface of a disc and, by applying the laws of heat diffusion, a calculation can then be made of the approximate surface temperature. At a depth of 2 millimetres below the surface it is normal to find temperatures of up to 800°C.



Definition of friction coefficient.

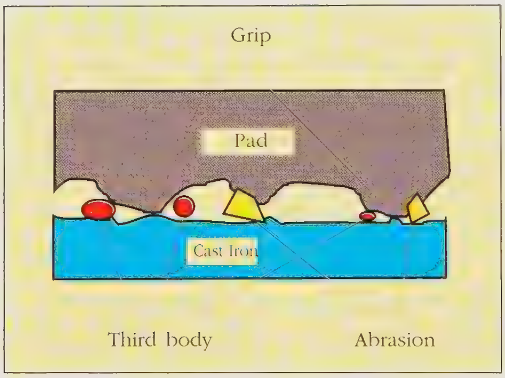


Disc heating as a function of thickness.

In addition to studying friction, tribology also investigates the mechanisms of **wear**. These play an important role both in braking and as far as maintenance costs are concerned. Again in the case of wear, adhesion and abrasion come in-

1.2.2 to play, since both lead to the detachment of micro-particles of the materials involved. These particles can be projected away from the friction interface in which case wear will propagate in a smooth, linear manner. When particles remain within the interface we speak of a *third body* due to which the rubbing mechanism and therefore wear is modified. The powders formed may be more abrasive or more lubricating than the original materials and therefore change the overall friction coefficient and braking performance. This is one of the reasons why brake pads have surface channels, the purpose of which is to facilitate elimination of such powders.

As far as the discs are concerned, there are other forms of deterioration that can resemble wear even though they are the result of completely different mechanisms. We are referring to cracking and corrosion.



Wear mechanism.

Cracking is essentially due to thermal shock although sometimes also to mechanical stresses. The very nature of cast iron and above all the disc's ability to dissipate heat are among the influencing factors. Cracks cause premature pad wear and at the same time cracking compromises braking safety as its expansion causes the disc to break. It can also occur at the joints between the surface and the carrier; in this case it is almost always a defect in the concept or assembly of components comprising the braking system.

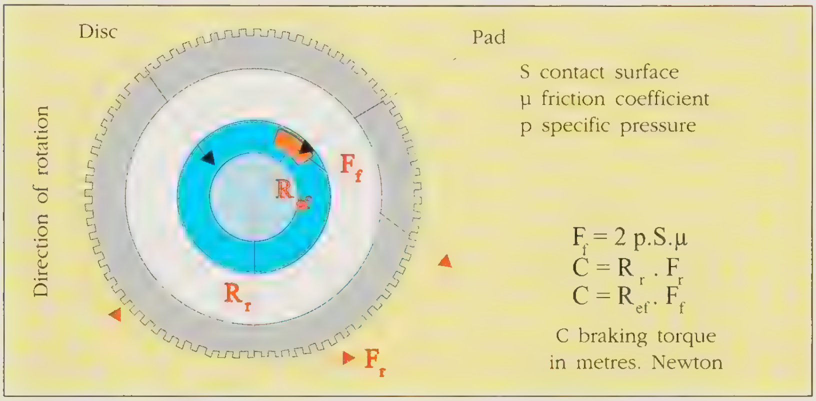
Corrosion is inevitable since cast iron is not rust-proof. It is caused by the action of oxygen when the disc surface becomes moistened by water, a circumstance that can be limited by providing the brake with appropriate protection from splashes. This solution, however, will be a compromise as there must also be no obstacle to cooling by means of air circulation. The effects of corrosion are rarely serious; it gives rise to a slight increase in wear and also causes noises and knocking following a prolonged period of inactivity. Usually the situation returns to normal after braking a few times since the surface oxidation that forms on the disc's braking tracks is eliminated.

1.2.3 PRINCIPLE OF DISC BRAKES

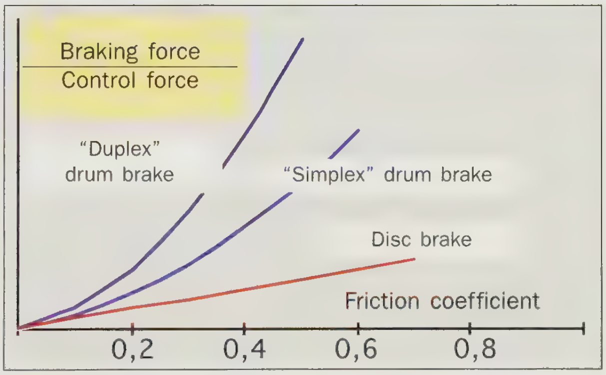
1.2.3

Disc brakes have gradually replaced drum brakes on cars throughout the world. All cars now have front disc brakes and, in increasing numbers, rear ones too.

Mechanics of the disc brake.



The principle of the disc brake is very simple: a metal disc with a diameter less than the wheel is firmly fitted to and rotates with the latter, therefore turning at the same speed. Two flat elements made of friction material - the **pads** - are secured to the axle and, consequently, to the chassis. However they run perpendicular to the disc and grip it when a force is applied. In which case the rubbing that occurs reduces speed and releases heat. The brake pads are positioned inside a caliper that has at least one piston which converts pressure into force. The torque of the force acting on the disc is transmitted entirely to the wheel. If the distance from the centre to the points at which the force is applied are known precisely it is then possible to calculate braking force at the wheel. As far as pads are concerned, this application point is located at the centre of gravity of the forces which it exerts on the disc. In the case of the wheel, this point coincides with the contact between the tyre and the wheel. The rolling radius is slightly less than that of the tyre itself since the latter is flattened by the action of the vehicle's weight.



Brake performance comparison.

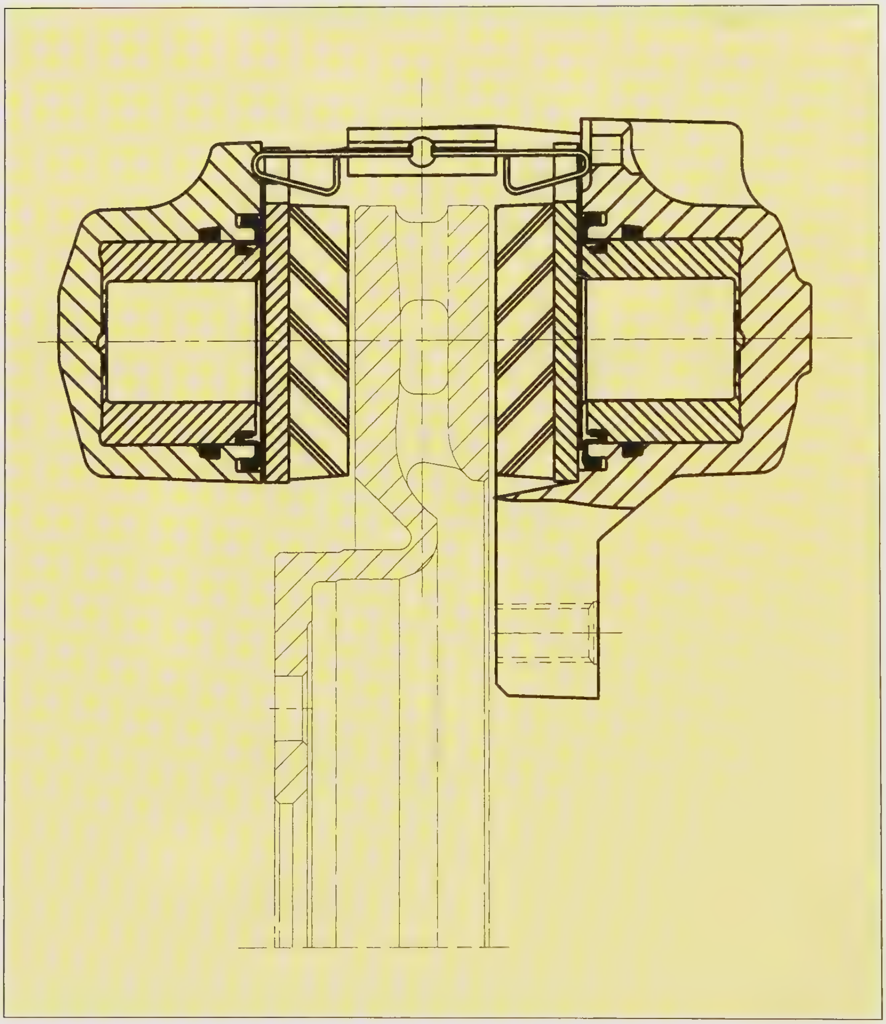
A brake therefore converts hydraulic pressure in the circuit, or more correctly the force exerted on the piston, into braking force at the rotor level, whether this be a disc or a drum. The conversion efficiency depends on brake technology and on the friction coefficient of the linings.

In the case of disc brakes this efficiency is proportional to the friction coefficient.

1.2.4 CALIPERS AND THE CIRCUIT

Distortion of the disc due to pressure of the friction material against its surface has to be avoided. The most obvious mechanical solution to adopt is symmetry and so one brake pad is positioned on either side of the disc, held in place by means of a metal element that straddles it. This is known as the **caliper**. The search for a compromise between performance, dimensions, comfort, weight and costs has led to the development of two families of caliper: fixed calipers and floating calipers. In simple terms, a **fixed caliper** is secured rigidly to the axle and has at least two opposing pistons that are activated by the same hydraulic circuit. This type of caliper is, incidentally, always hydraulic. As pressure is exerted the two pistons advance towards the disc; when the first brake pad makes contact it stops; it is then the turn of the second pad to make contact and only at this moment do the gripping forces increase. In reality such movements are minimal, in the order of a few tenths of a millimetre.

Diagram of a fixed caliper.



The **floating caliper** functions like a vice, that is, when one of the pads rests against the disc, by reaction the opposite pad automatically makes contact with the other side. This presupposes however that the caliper can move in order to centre on the symmetrical plane of the disc.
Normally this type of caliper has only one piston and can be controlled either hydraulically or pneumatically (in the case of brakes on heavy trucks). Certain floating calipers have two pistons, but these are located on the same side. When pres-

1.2.4

sure is applied the piston advances until the brake pad makes contact with the disc. At this point, pressure is applied at the base of the piston cylinder, causing the entire caliper that, as mentioned, is free moving, to retract. When the second brake pad comes into contact with the disc then the gripping action begins. Although the movements are small, the freely moving caliper - fixed to the axle by means of studbolts - must have a certain amount of freedom so that it can position itself correctly in relation to the disc without significantly forcing against its point of attachment. It is also necessary that the latter be sufficiently solid in order to avoid rotation of the caliper together with the disc. Compared to a fixed caliper the piston in this system has twice the degree of movement. This type of caliper is noisier because it is less rigid and therefore has more chance of vibrating. It is slightly less efficient than the fixed caliper in as much as part of the force is absorbed by rubbing action due to slipping. This difference is most noticeable at high pressures.

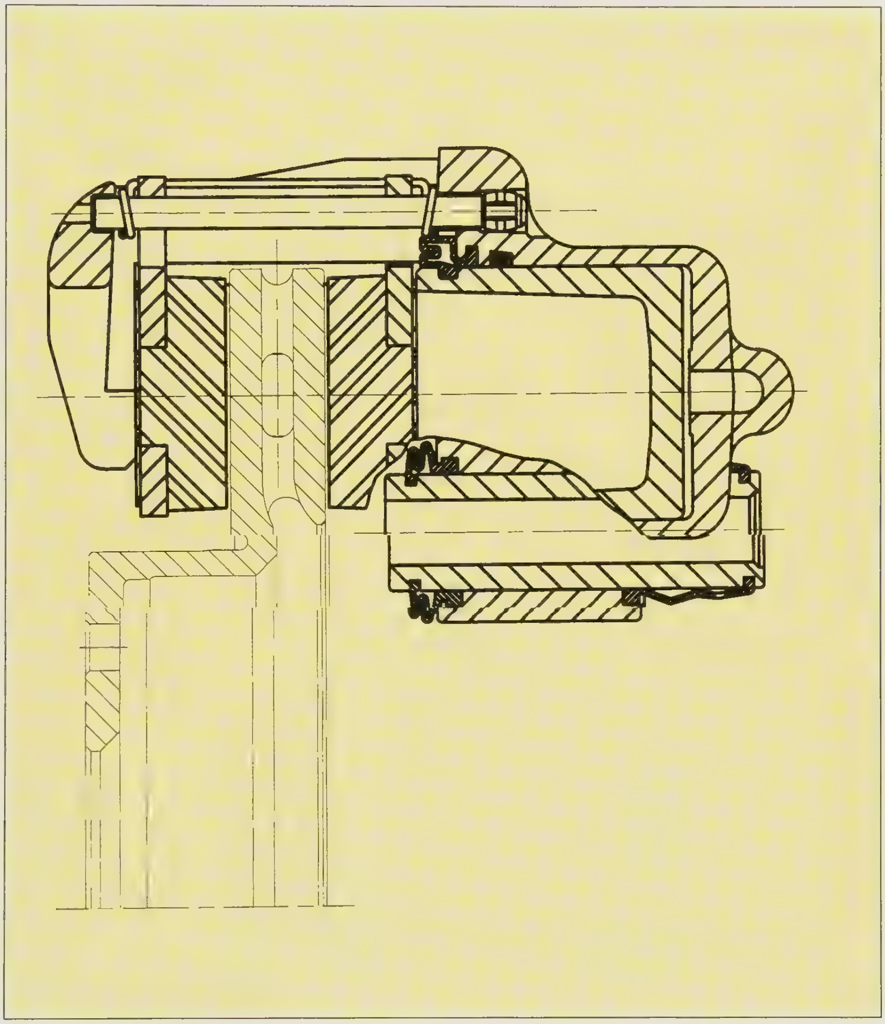


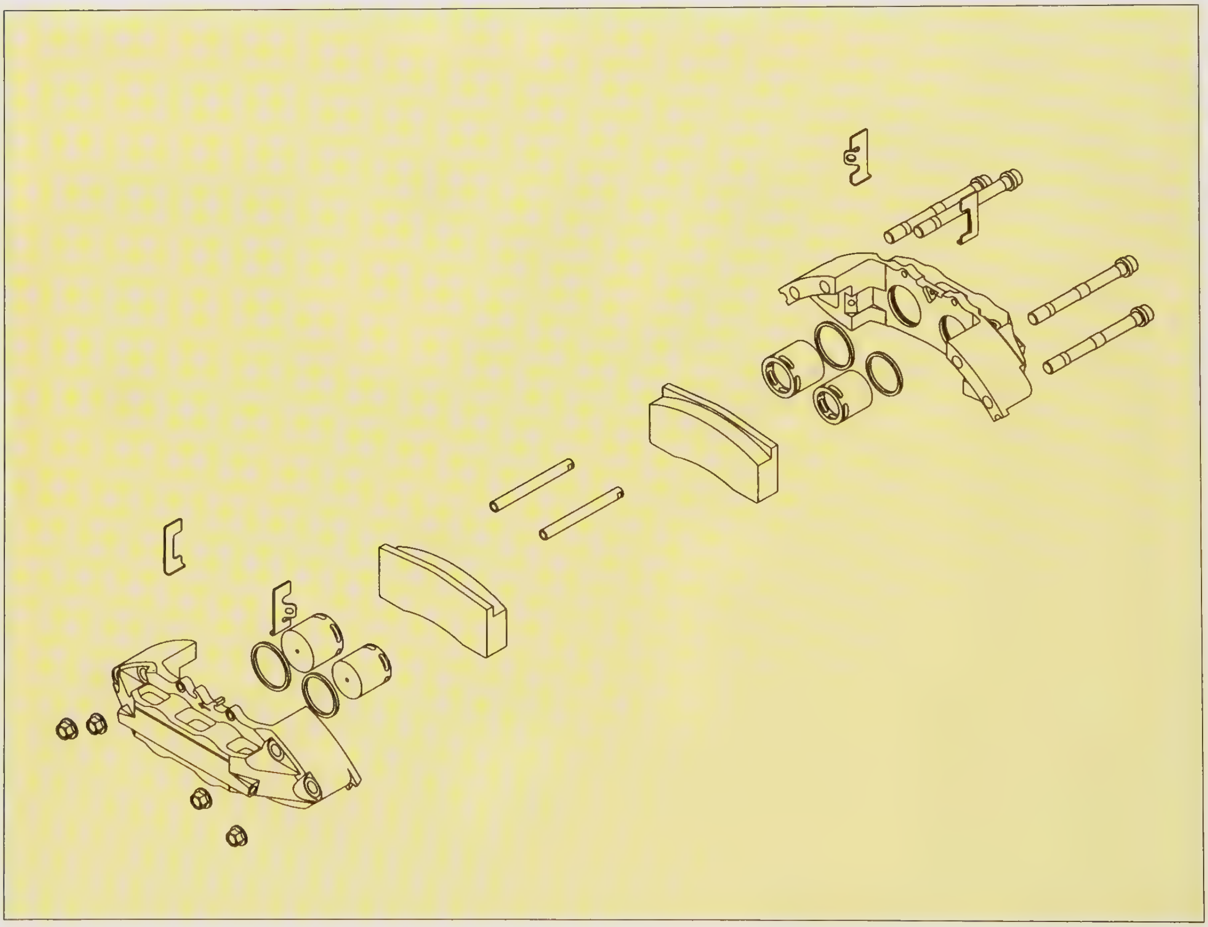
Diagram of a floating caliper.

Calipers such as these are subjected to very strong forces and are produced from spheroidal cast iron although, wherever possible, the tendency is to use an aluminium alloy in order to reduce weight. These alloys are much lighter and are also much better heat conductors: 220 W/m.°K for aluminium compared to 44 W/m.°K for cast iron. This means great care must be taken to avoid overheating the brake fluid which could lead to its boiling.

1.2.4

The calipers can be positioned at the front or rear of the disc. If the disc were a clock, ideally the calipers should be positioned at either 9 or at 3 o' clock. The position is selected both to make it easier to bleed the circuit and to reduce the effect of disc wobble when cornering which tends to cause pistons to retract into their cylinders.

Exploded view of a caliper.



After braking, the pads must retract and break contact with the disc otherwise they would continue to rub against it slightly, causing abnormal wear and noise. Rarely metal springs are used for this purpose. The gaskets around the pistons have a collar-like shape expressly designed so that the piston can retract or **Roll Back** into its cylinder once pressure ceases.

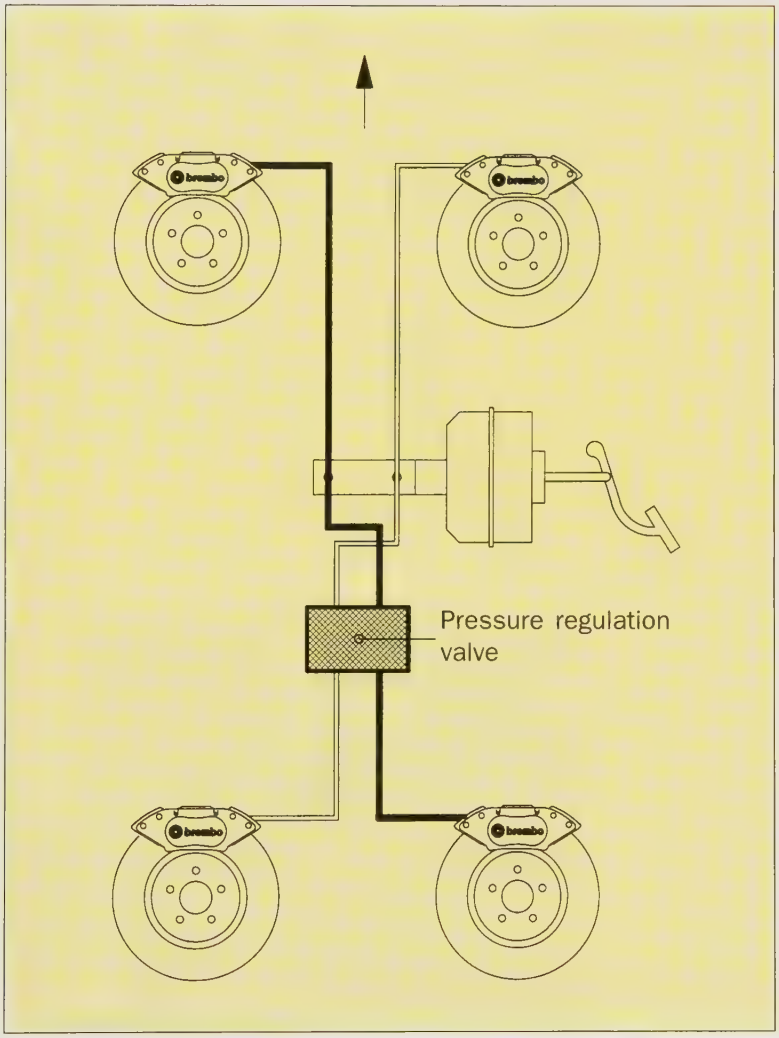
Various features are included that supplement the caliper's primary function. **Play recovery** blocks the piston so that it cannot roll back more than a few tenths of a millimetre. In fact, as the brake pads gradually wear down, the piston advances within its cylinder. If, for example, a knock were to cause it to retract, fluid

1.2.4

would flow back towards the brake master cylinder and the next time the brake was used it would probably be inefficient.

The **parking brake**, or handbrake, is a mechanically controlled device that is normally an integral part of the rear brake calipers. One of the most widely used technologies is a small drum brake positioned within the disc carrier (Drum in Hat).

Diagram of a braking circuit.



With the exception of disc brakes on heavy trucks that have pneumatic control in combination with mechanical transmission, car brakes all have **hydraulic control**. Besides the calipers, the system includes the following components: the master cylinder, the fluid tank, distributors, the braking corrector, rigid and flexible hoses - without forgetting, of course, the brake pedal and its rods. Many cars have a brake **servo**. The force exerted by the driver on the pedal is amplified from 3 to 4 times as a result of the vacuum created by the engine's air intake. **ABS** control is achieved by means of electro-valves fitted within the circuit. The maximum fluid pressure within the circuit is usually 80 bar, although circuits do exist that can operate up to 175 bar.

The **fluids** used are mostly obtained by organic synthesis and must meet certain safety criteria. They must be stable, that is they must not decompose as a result of temperature changes or over time. Their boiling point must be very high, in the order of 250°C. Lastly, they must have very low hygroscopic properties - the fluid's capability to absorb water vapour - as in fact water lowers the boiling point of the fluid with the risk that "vapour lock" may develop.

When this happens, it is most serious. Overheating of the fluid causes it to boil

1.2.4

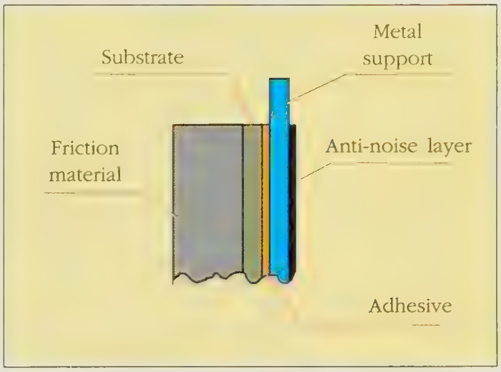
and gas bubbles from within the circuit. The more the fluid deteriorates as a result of absorbing water, the lower the boiling point becomes. The pedal becomes slack and the force exerted on the pads is insufficient to brake. In order to avoid the onset of this phenomenon the brakes are cooled efficiently and the pads have thermal insulation. It is also necessary to change and bleed the brake fluid from time to time, as indicated in the vehicle maintenance manual. Finally, if the quantity of water is excessive at low temperatures it can separate out from the fluid and form ice which in turn can cause the brakes to not function normally.

1.2.5 BRAKE PADS

1.2.5.1 STRUCTURE AND GEOMETRY

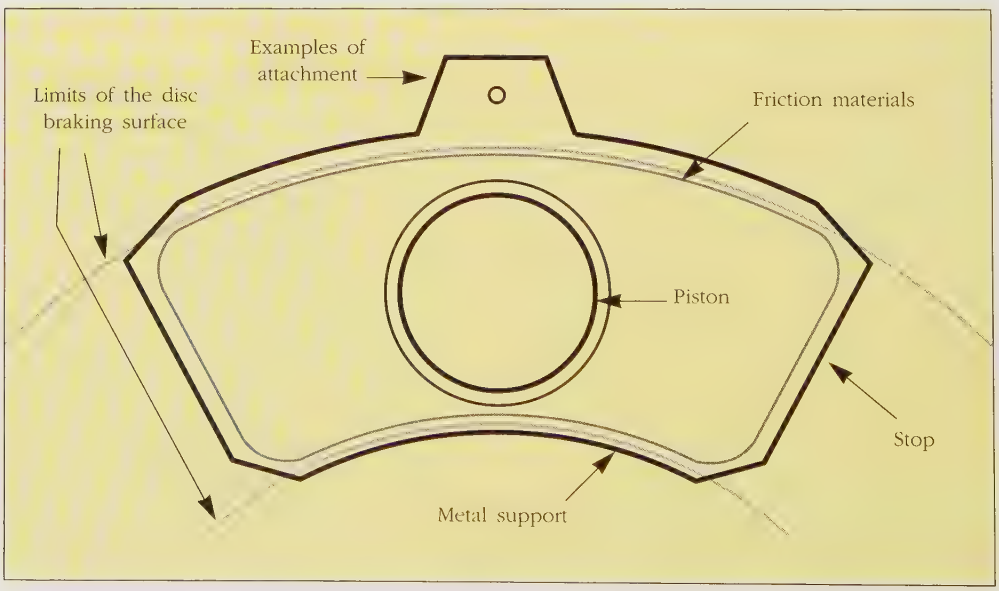
The pad is essentially a piece of material designed to rub against the disc surface in order to convert mechanical energy into thermal energy. In this sense it is no different from the linings in a drum brake. Its distinguishing feature, however, is that the friction surface is flat. We can imagine calipers where pads are nothing more than a piece of friction material. In reality the pad is rather more complicated as it is made up of numerous parallel layers produced from different materials. The thickest layer is the true **friction material** that comes into contact with the disc and gradually wears down. On the opposite side is the **support** or **plate**, a flat plate of mild steel about 5 mm thick. Its main purpose is to distribute the force exerted by the piston over the pad's entire contact surface. In fact friction materials are quite fragile and subject to breakage; the direct contact of the piston on a limited area would risk damaging them. The thickness of the support is therefore calculated so that under maximum force it has an imperceptible flexing distortion that does not cause the material to wear unevenly. The purpose of the support is also to secure and position the pad. In partic-

Section of a pad.



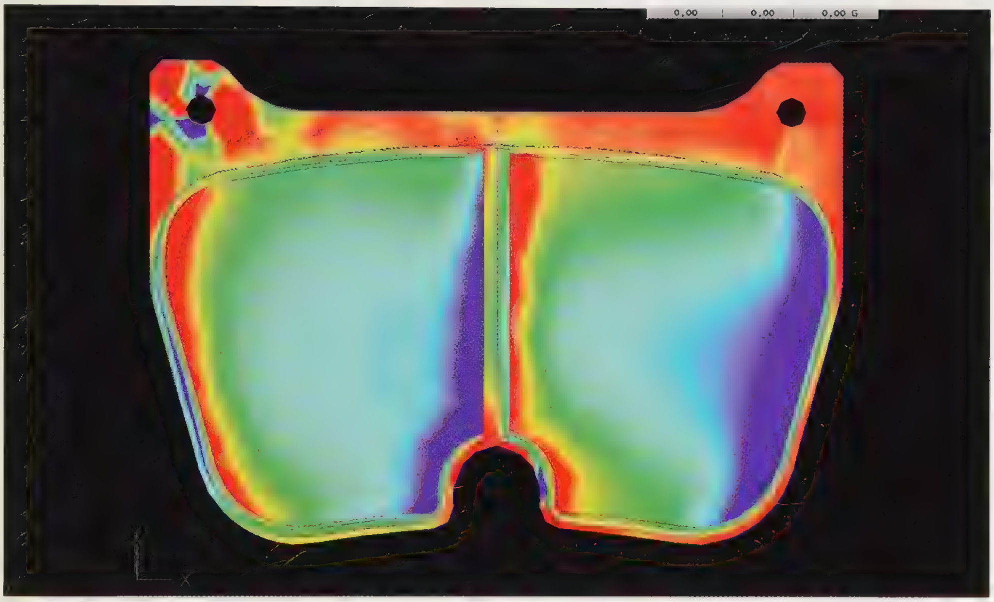
1.2.5.1 ular, sections of this metal plate rest against the caliper during braking. This is because the disc tends to drag the pad in the direction of rotation. Many types of pad have an additional layer about 2 mm thick between the support and the friction material: this is known as the **substrate**. It has a number of functions: it bridges the dilation coefficients of the steel and the lining, it acts as a thermal insulator so preventing an excessive flow of heat towards the piston and brake fluid, it absorbs noise and vibrations. This layer does not have a friction function as it is mandatory for the pad to be replaced before wear exposes it. During production a layer of **adhesive** is interposed between the substrate and the support in order to improve the adherence: the quality of the adhesive is most important as it conditions the pad's cutting resistance. Behind the support there may also be a sheet of what is usually rubber coated steel - an **anti-noise layer** which has the function of minimising the transmission of vibrations. After manufacture most pads are fitted with a wear indicator that normally consists of an insulated electric wire which comes into contact with the disc when the maximum pad wear level is reached. The shape of the pad is a compromise between two types of geometry. Firstly, the pad must rub against the disc surface and therefore its natural shape is a section between two arcs of a circle. The piston has a circular section; the isobar curves are therefore circumferences. This shape enables a balanced distribution of forces

The shape of a pad is a compromise between two geometrical forms.



to be obtained. The definitive form is the result of this compromise, but it is also based on calculations. Calculations performed on finished elements not only make it possible to determine pressure distribution but also provide use-

ful information relative to both localised stresses that may possibly cause breakage, and heat diffusion. 1.2.5.2



Finite element modelling of a pad. The red area is that subjected to higher pressure.

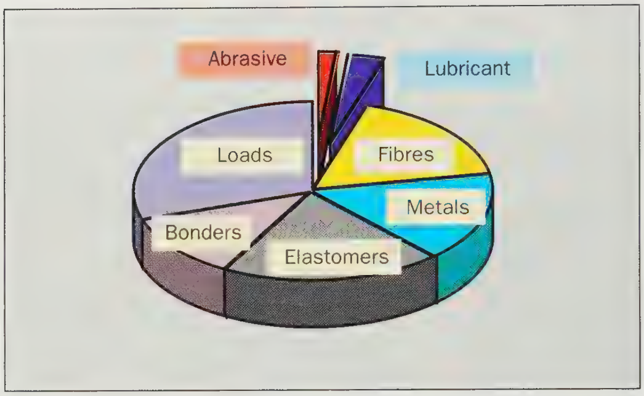
1.2.5.2 COMPOSITION

In order to understand the relative complexity of pad composition reference must be made to specifications summarising the qualities required. In addition to basic geometrical and mechanical aspects the concepts of safety, comfort and economy play a part. As each vehicle differs from others in this respect it is often necessary to develop a product that is exactly suited to a new model. This takes place during the vehicle development stage and is the result of a long series of modifications and tests.

Main elements in a pad specification	
Mechanical	**Comfort**
Hardness	Braking behaviour
Squash resistance	Grip
Cutting resistance	Noisiness
Safety	**Cost**
Friction level	Production cost
Pressure sensitivity	Pad wear
Speed sensitivity	Disc wear
Temperature sensitivity	Corrosion
Water sensitivity	
Thermal transfer	

1.2.5.2

Volume composition of a pad.



When describing the composition of today's pads in detail it is difficult not to refer to old formulas that contained a large proportion of asbestos. This component, now no longer present in European products, had a profound effect on how friction products were conceived and used. Asbestos is a mechanical and heat-resistant mineral fibre. However, as it was not replaced by an alternative material, it became necessary to modify the composition of friction materials considerably. Furthermore, simultaneous with the disappearance of asbestos-based products, new needs made themselves felt as regards safety and comfort. It is therefore difficult to compare old and new products since, seen overall, the latter have substantially improved properties.

The composition of products clearly also depends on the company conducting the research and producing them. In spite of this, the same broad categories of constituent substances are found in all formulations: active products, diluters, modifiers and consolidators.

The components that confer the main braking properties are the solid **abrasives** and **lubricants**. In the composition these components are normally never of one single type as certain are more active when cold and others when hot. A number of very abrasive or very lubricating compounds are added to the mixture in order to achieve the ideal balance. As in the case of pharmaceutical products, these active elements are *diluted* using mechanical and chemically resistant **loads**, however, which have only a slight abrasive or lubricating action as far as cast iron is concerned. The physical properties of this initial mixture are modified by the addition of **elastomers** that give the product a certain elasticity and reduce its rigid and fragile nature. Heat transfer properties are also modified by adding **powders** or **metal fibres**.

Consolidation of this mixture - essentially comprising powders - is achieved by adding **fibres** which are the reinforcement of the finished product. Lastly, a **binder** is required that can bind these various particles together so that the mixture becomes a compact solid. The basic binder used by all manufacturers is a thermo-hardening phenolic resin.

Examples of components found in brake pads

Abrasives
- Alumina
- Zircon sand
- Silicon

Lubricants
- Graphite
- Sulphides

Loads
- Marble
- Rocks

Elastomers
- Natural latex
- Styrene butadiene
- Nitrile

Metals
- Steel wool
- Copper
- Bronze
- Brass

Fibres
- Aramide
- Polyacrylic nitrile
- Glass
- Glass wool

Bonders
- Resins
- Novolac resin

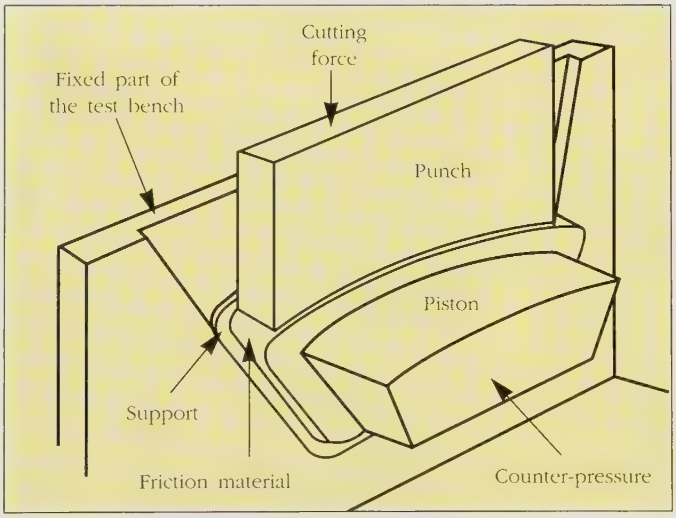
1.2.5.3 PRODUCTION AND QUALITY

The first stage of pad production involves establishing the **mix** and quantities of the various constituent elements. This stage has to be monitored very carefully; quantities must be extremely precise and care must also be taken to avoid confusing or exchanging one component for another. In fact, certain components - for example the abrasives and lubricants - are very active and an error in their quantity would radically change the performance of the finished product.

The mixture must then be shaped and hardened. **Shaping** consists in giving the friction material its definitive shape and bonding it to the support. **Curing** is a thermal process during which the resin melts, impregnates the particles and then hardens to form a solid. In simple terms there are two processes: the first, known as press-forming, consists of pressing the powder at a very high pressure (1000 bar), followed by treating the pads obtained at a temperature of around 150°C in special ovens. In the second process, the two operations are carried out simultaneously; the pressure is lower (400 bar) and the temperature higher (170°C). In this case the pads remain in the press for a longer period, hence the name press-curing that is given to this process.

Among the finishing, machining, coating operations, etc. there is also pyrolysis treatment of the surface. This treatment, known as scorching, is carried out by exposing the surface to a flame or by placing the surface against a plate heated to 700°C, where the purpose is to partially destroy the resin in the first few millimetres below the surface. This ensures that the pads provide good friction performance right from the very first braking actions. In fact, thermal breakdown of the resin would seriously affect the friction coefficient (fading). Based on current quality standards a number of checks are performed throughout all stages of production. Other checks are carried out at the end of production, either on all or a sample of the pads. All pads are examined for visible defects (cracks, breakage or irregular coating). Pads showing such defects are discarded. Among the sample checks performed, mention should be made of that concerning composition, normally carried out using the X-ray fluorescence technique, and the measurement of **cutting resistance**. In order to perform the latter measurement, the pad is first positioned in a device that grips it by the support side. Pressure is then exerted on the friction material layer by means of a piston. This tests whether the pad resists the cutting that occurs when it is fitted to the caliper and is subjected to cutting forces. At

Cutting test.



1.2.6

ambient temperature cutting of the friction material or the substrate must occur at values greater than 30 daN/cm^2 of pad surface. Values less than this level are an indication that the entire production batch must be discarded.

1.2.6 BRAKING TESTS

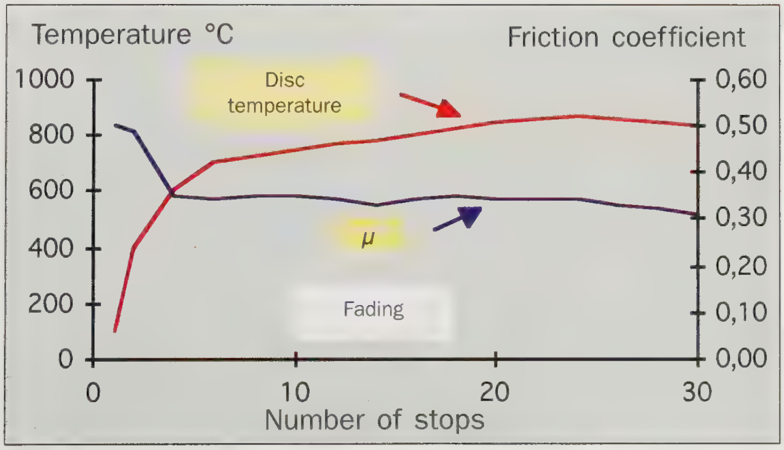
The disc brakes we have described comprise the following elements:
- caliper,
- piston(s) and respective gaskets,
- disc,
- pads,
- brake fluid.

Clearly there are specific tests for all of these elements the purpose of which is to evaluate their conformity and performance. We will examine specific disc tests later.
There are also overall tests to verify the performance of the brake as a whole. These consist of simulations of braking, either performed in the laboratory or on the road. It should however be noted that pad quality plays a preponderant role as far as the results obtained are concerned. Tests conducted on vehicles clearly provide results closer to reality. However, such tests have certain drawbacks. First

Dynamometric test bench.

of all it is extremely difficult to test only the brakes as the vehicle, and especially the wheels and suspension, affect the results. Furthermore, the test results depend partly on climatic conditions and the state of the road. Lastly, vehicle tests are very time-consuming since a running-in period is first necessary and this takes the tester more time.
This is why we always start with a series of tests that use automatic control rotary equipment during which results are recorded and then processed. There are various types of testing equipment. The most representative is the dynamometric bench, known as the **dynamometer**. The characteristic feature of this type of equipment is that it stores kinetic energy within inertia fly-wheels which rotate at the same speed as the wheel and which are stopped by a brake mounted on the same shaft.
As on a vehicle, the brake is controlled by a hydraulic circuit, but the pedal is substituted by a solenoid and so operates according to predetermined pressures.
Each testing procedure has a precise aim: measurement of wear, noise, etc.
The more frequent types measure brake **performance** under various conditions: when the brakes are cold, or hot and at high speed. In order to do this, the equipment is able to establish speed, pressure and braking duration. It measures parameters, namely braking torque, temperature and braking time. Thanks to these values it is possible to calculate many others such as the friction coefficient for the pads as compared to that of the disc.
A complete **testing procedure** is a sequence of various interconnected phases, each of which has a specific aim (for instance, measure sensitivity to speed, to pressure or temperature).
In this latter case a rather sharp braking action is applied and repeated regularly at close intervals. It can be noted that the temperature rises. Starting from the mechanical results the friction coefficient is then calculated. This can be seen to remain generally stable up to 350°C, before falling in a more or less pronounced manner. This phenomenon is referred to as *fading*.

Trend for the friction coefficient as temperature varies.



Final homologation of a braking system or one of its components is normally the result of tests on the vehicle for which the brake has been developed. This is why, in spite of the fact that such tests are both long and costly, we proceed sys-

1.2.6

Test vehicles are equipped with computers.

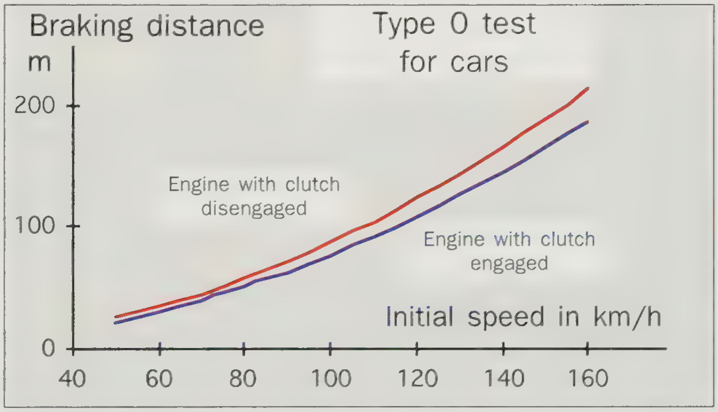
tematically with numerous tests on vehicles. Procedures vary according to car manufacturer, but in Europe homologation tests are harmonised and scrupulously adhere to the EU directive.

Test vehicles are equipped with a computer that indicates the sequence to be followed by the driver, performs braking measurements and lastly calculates and produces the results. A "fifth wheel" is used in order to obtain exact measurements of effective vehicle speed and the distance travelled. This is in fact a bicycle wheel fitted to the side of the vehicle that has no weight bearing on it. In fact the squashing of the tyre and its slip with respect to the road invalidate speed measurements as indicated by the speedometer. If the contact of the fifth wheel with the road surface is regulated properly then there is no slip.

A "fifth wheel" is used to measure speed exactly.

1.2.7 EUROPEAN REGULATIONS

Regulations concerning car manufacture, and in particular as regards brakes, were initially established at United Nations level in Geneva and later by the European Union in Brussels. The aim of these regulations is twofold: first, and most obviously, that regarding safety; whereas the second and more important aim is to enable the free circulation of goods within the **EU**. In fact when a product has been homologated in accordance with European regulations, no member country can make its own regulations more restrictive in an attempt to limit sale and use of the product concerned. Regulations issued by the **UN** concerning braking are identified by the references **R13** and **R90**. The EEC issued a number of directives between 1971 and 1991 that complete the basic regulations as far as the brake field are concerned, identified by reference **71/320/EEC**.



Type 0 standardised European test.

This directive has a rather brief introductory text and 12 technical annexes that give a very detailed description of the standards that vehicles and braking systems must meet in order to be homologated. The majority of these annexes concern the transport of people, heavy trucks and their trailers. For cars that transport less that 9 people (type **M1**), *annex 2* applies, which details the performance to be reached, *annex 10* refers to anti-locking devices and *annex 12* describes the dynamometer testing method for brake pad homologation.

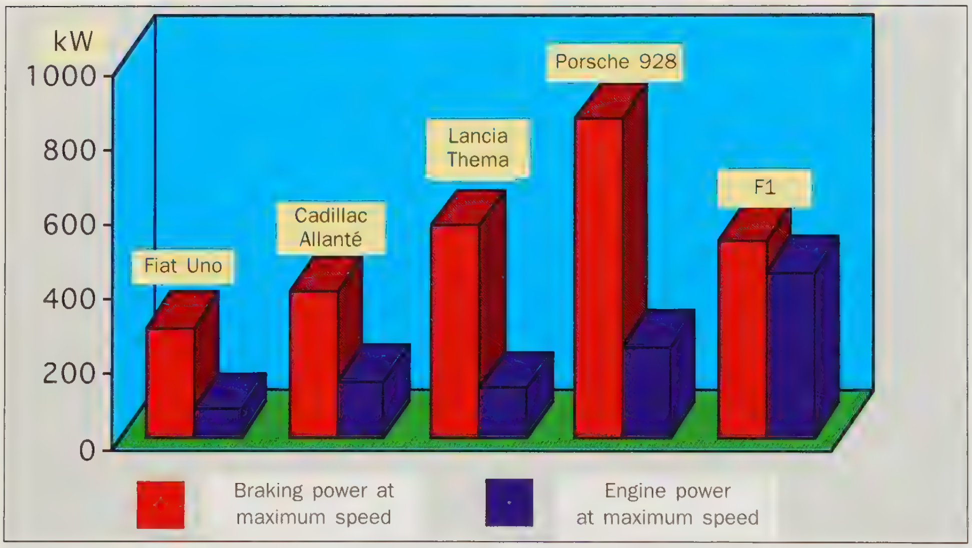
Annex 2 establishes the tests to be performed and minimum performance to be reached for all types of vehicle.

In **type 0** tests, braking distances are measured with cold brakes and at an initial speed of between 30% and 80% of the vehicle's maximum speed. This test is carried out both with the clutch engaged and disengaged.

The **type I** test with hot brakes is performed after braking 15 times at 45 second intervals and starts from 80% of maximum speed.

Furthermore this annex describes tests for parking brakes and establishes that a vehicle must remain immobile on a slope of 18%.

We have seen that a brake can be considered a system that converts kinetic energy into thermal energy. At the same time we can note that the power output required of brakes is considerable and greatly exceeds that of the engine, even though it remains proportionate to the latter. This varies with the speed and the weight of the vehicle but also depends on driving style and the manner of braking, as data relative to Formula 1 indicate. The device required to achieve this must have a mobile part and a fixed part. As it is the more simple, the mobile part is cylindrical in shape. For a long time the rotating part really did have the shape of a hollow cylinder, namely a drum. For several reasons, but particularly because its functioning is more stable, the disc brake has rapidly affirmed itself, replacing the drum brake on front axles. The rotating part is still cylindrical - although the height is much reduced - and the pads act by rubbing against both of the end surfaces. Often both types of brake can be found on the same vehicle although the current trend is to fit both front and rear disc brakes. This is already a reality for top-level cars but also for many other models in as much as in 1997 one car out of ten had four discs.



Braking power/engine power comparison.

The disc is an essential part of this brake and the criteria to be considered during its design are many. The **dimensions** must be consistent with the maximum quantity of energy exchanged when braking. **Wear** must be minimal, while reliability is a fundamental safety factor. Like all rotating components the disc can be a source of vibration. The level of **comfort** that drivers demand from a modern car requires in-depth study and severe control procedures during the production phases.


brembo

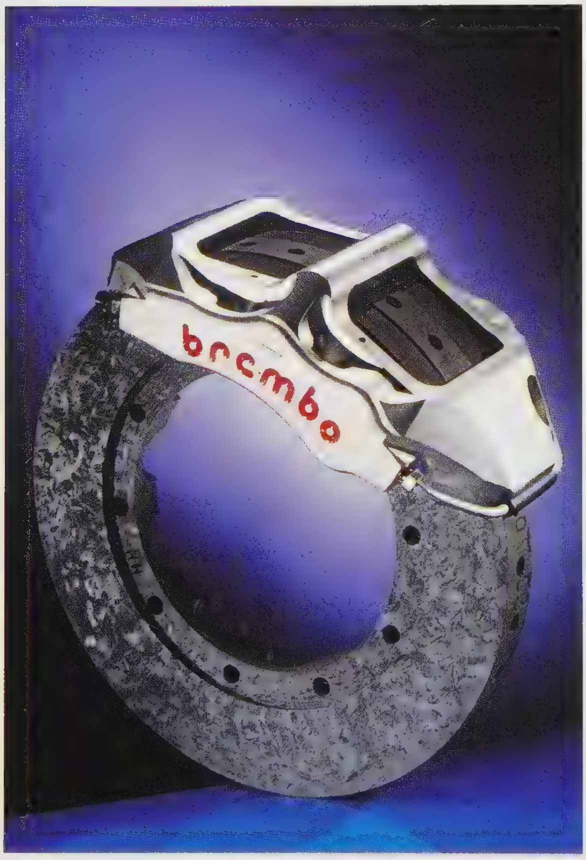
2.1

2.1 CHARACTERISTICS OF A DISC

2.1.1 COMPOSITION

The two main functions of a brake disc or drum are the transmission of a considerable mechanical force and dissipation of the heat produced, that implies functioning at medium or high temperatures. From a theoretical standpoint numerous materials would be able to fulfil these functions. In reality, for reasons of performance stability, cost of raw materials and ease of production, cast iron is the material universally used. However, other materials are used for specific braking applications. For example, composite carbon matrix materials are employed in the production of brake discs for competition cars and aeroplanes, although their particular performance level and cost make them inappropriate for use on standard vehicles. Also aluminium alloys containing silicon carbide can be considered as they afford a significant reduction in weight, although their inability to support high temperatures means that brakes have to be oversized, a factor which partly cancels out the weight advantage. Cast iron in one of its numerous forms therefore remains the preferred material.

Formula 1 carbon disc.



2.1.1.1 CAST IRON

Cast iron is the first product obtained in steel making when smelting iron ore. It is the result of the reduction of ferrous oxides under the action of the carbon in metallurgical coke. Molten cast iron is in reality a carbon solution in molten iron. When it is cooled a very small part of the carbon remains in the ferrous solution whereas the majority of it precipitates to form small nodules scattered throughout the structure of the metal. Usually this unrefined cast iron is not suitable for the majority of applications but must undergo both physical and chemical processes in order to create the vast and well-known range of ferrous alloys. The main products are the many types of stainless steel, cast iron and mild steels which have a very low carbon content and are widely used because of the property whereby they can be shaped by means of bending and rolling.

Cast iron is defined as any alloy with a greater than 2% carbon content. In stan-

2.1.1.1

	% carbon content	Main additives	Melting point temperature	Brinell hardness
Mild iron	0,1-0,2		1500°C	50
Construction steel	0,4-0,5	1%Mn 1%Ni 1%Cr	1450°C	100-200
Tool steel	0,8-1	2%Mn 3%Cr	1400°C	100-200
Stainless steel	0,2	8%Ni 18%Cr	1455°C	320-380
White cast iron	3		1300°C	400-600
Grey cast iron	3,2-3,7	2%Si 0,4%Mn	1200°C	170-270

dard cast irons this content is always more than 3% in terms of weight. It is this that gives the material a special structure since carbon - hardly soluble at all in a solid state in iron - precipitates under various forms and, given its density, represents between 12-15% of total volume. This high carbon, and above all graphite content gives the alloy good thermal conductivity, but also a certain fragility. Three broad families of cast iron can be identified. **White cast iron** is very hard, breaks easily and is difficult to work. **Nodular** or **spheroidal grey cast iron** contains, as the name indicates, precipitated carbon in the form of small nodules. **Lamellar graphite grey cast iron** is the most common type and is used for the production of discs and drums in braking systems. As can readily be observed in the micrograph analyses, the graphite is present in the form of small plates that seem like threads as they are only seen in section.

Micrographic examination of lamellar structured grey cast iron. x100 magnification.

These various cast irons all have a rather similar composition and therefore the actions taken to obtain the different structures involve the additives and, above all, thermal treatment conditions during the processing and cooling stages. In order for the product to be considered good quality for disc production it must be homogeneous from the micrographic standpoint: thin plates of **graphite** dispersed in the perlite.

Perlite itself is a succession of very thin **cementite** (Fe_3C) plates within the **ferrite**, that is to say, a very pure iron. Cast irons that contain large inclusions of only ferrite or cementite are discarded. In fact cementite has a very high hardness rating, equal to more than 650 HV1

2.1.1.2

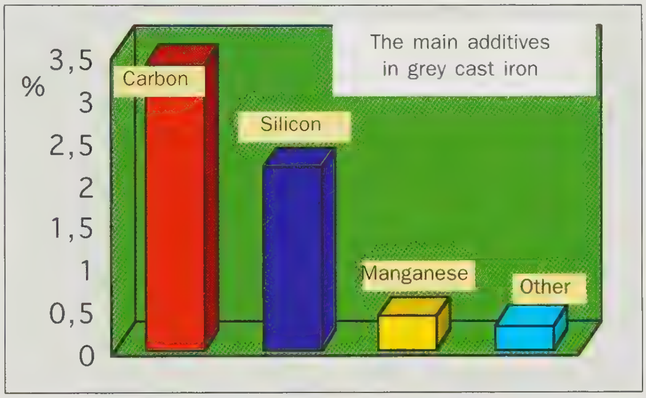
(VICKERS hardness scale that corresponds to 750 HB on the BRINELL scale). Its presence would create localised hard points and make it inappropriate for friction material as these would act as a powerful abrasive. On the contrary ferrite has a hardness of around 100 HB, much lower than that of cast iron which is about 200 HB. Another factor that comes into play in friction is the dimension of the graphite plates that normally range between 15 µm and 500 µm. The arrangement of these plates must be random as opposed to organised. The latter case can arise during the disc production process if cooling is not properly controlled. The cast iron becomes fragile and discs made from it are not appropriate for use.

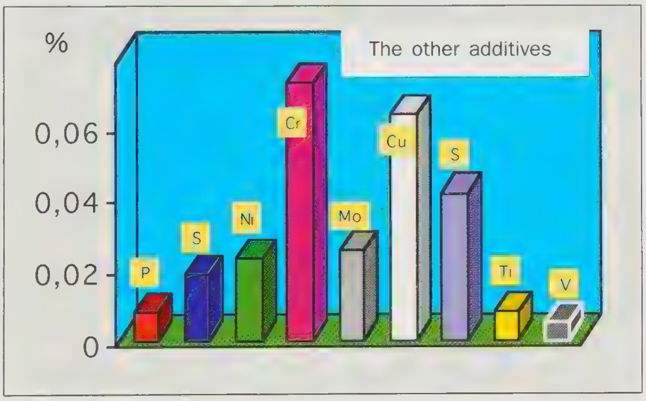
2.1.1.2 SPECIAL CAST IRONS

A cast iron can be characterised by a large number of chemical and physical parameters. For brake disc applications, however, only a limited number of these are normally taken into account and are closely linked to its use. Grey cast iron, less fragile than white cast iron, is however not malleable or ductile enough. Elasticity is minimal and it rapidly reaches breaking point. The value for **breaking resistance** varies on the basis of composition and structure, but the order of magnitude is 25 daN/mm^2. This value is checked systematically and is also necessary for standardisation. The same can be said for **hardness** which is much easier to measure and much more representative of the structure and homogeneity. As far as grey cast irons are concerned the Brinell hardness values lie between 170 and 250 HB. Other parameters are measured indirectly: for example, casting, machining and milling properties, or capability to dampen vibrations and therefore noise. It is in fact possible to measure the **Young dynamic modulus** and the **damping factor** for samples or perform overall measurements on finished discs.
It can be noted that for every type of vehicle and disc it would be necessary to use a type of cast iron with specific properties. Although this is not always possible, numerous qualities of cast iron are used, depending on the specific characteristics required. This choice is part of a brake disc designer's know-how.
Two aspects come into play when modifying a cast iron: its composition and thermal treatment during casting.
A typical grey cast iron contains between 93-94% of iron in the mass. This **iron**, plus the three main additives, constitutes more than 99.5% of the overall mass, although this does not mean that the remaining additives do not play a part. In addition to **carbon** - the main additive in the alloy - we find **silicon**, the content of which must be carefully controlled because although on the one hand it has

2.1.1.2

the benefit of improving casting properties, on the other it also reinforces graphitising and increases fragility. Metallurgical experts usually speak in terms of **carbon equivalent** content. Certain additives in fact fulfil a similar role to that obtained by increasing the carbon content. In the case of the carbon illustrated here, the carbon content is 3.35% whereas the carbon equivalent content is 4.1%. **Manganese,** found as a result of the metallurgical process, must only be present in very limited quantity. In fact this element combines with sulphur to form Manganese sulphide (MnS) that gives rise to very hard, abrasive granules which, in addition, make machining very difficult. The maximum manganese sulphide content is 1%. Other elements found in the alloy are almost always the result of impurities in the ore or the compounds used in casting. **Nickel**, **chrome** and **copper** in particular all affect the metallurgical structure and therefore hardness. Their content normally does not exceed 0.2% although certain nickel or copper-rich cast irons have been developed to satisfy specific technical requirements. Depending on the quality of cast iron sought, the maximum and minimum values for additive content must fall within a very narrow range or the batch concerned should be immediately discarded.



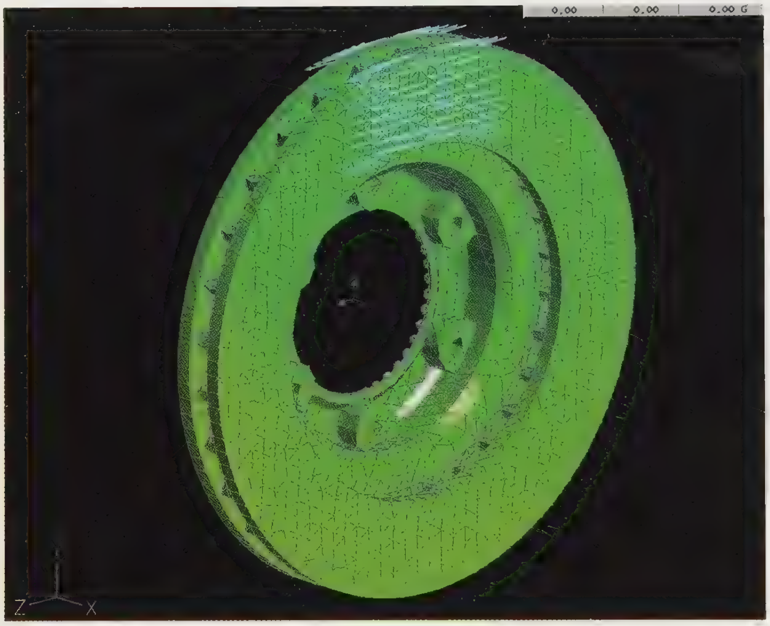


Basic composition of a grey cast iron.

2.1.2

2.1.2 SHAPE

While it is true that some discs were and still are produced according to simple, flat and circular geometry, their shape is normally more complex and can be broken down into a number of parts, each corresponding to the particular function performed.



Finite element analysis view of a disc.

The **braking surface** is the area on which the braking action of the friction material takes place. Dimensions are such as to ensure that the specific power output is not too high. A value of 230 Watt per cm^2 of braking surface is the basis for calculating size, although this value can change considerably when the disc is very well ventilated and can reach 623 Watt per cm^2.

The second function is that of **attachment** provided by the central part of the disc which has a circular aperture which serves to centre the wheel axle. The central part of the disc is surrounded by a number of holes for the hub screws and wheel bolts.

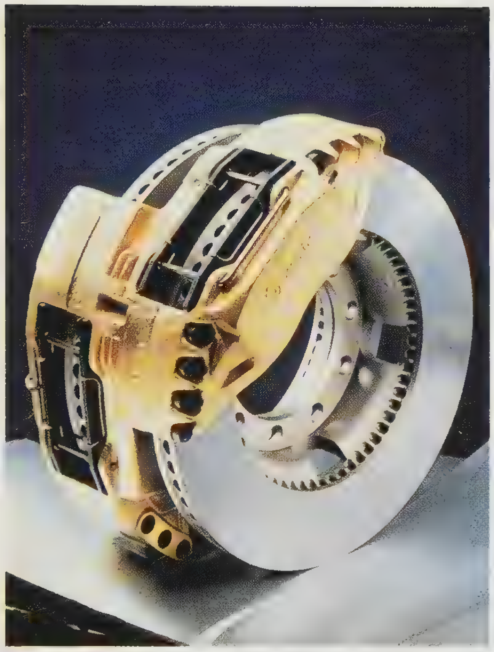
The part that serves to connect the braking surface to the central part almost always has the shape of a horizontal cylinder. This part, together with the central part, is referred to as the carrier or the **hat** because of its shape.

The internal surface of the carrier is often used to fit a small drum brake, usually a parking brake, that, as mentioned previously, is known as the **Drum-in-Hat** technique.

As we will see later, most of the heat produced in braking is transferred to the disc. Since the latter cannot accumulate an infinite quantity of heat, a way of dissipating it must be devised. The most simple manner is to ensure circulation of air which heats up when in contact with the disc and keeps the temperature at an acceptable level in order to keep it intact.

The disc is therefore required to perform two additional tasks: induce air movement like the rotor in a centrifugal fan and, simultaneously, act as a heat exchanger like a radiator. The circular shape of a disc makes it particularly well suited to this dual role. In fact as the disc rotates it sets in motion the laminar stratum of air with which it is in contact. The external part of the disc rotates at a greater linear speed than the part near to the carrier or hat. Here, dynamic pressure acting on the air is greater in as much as it varies with the square of

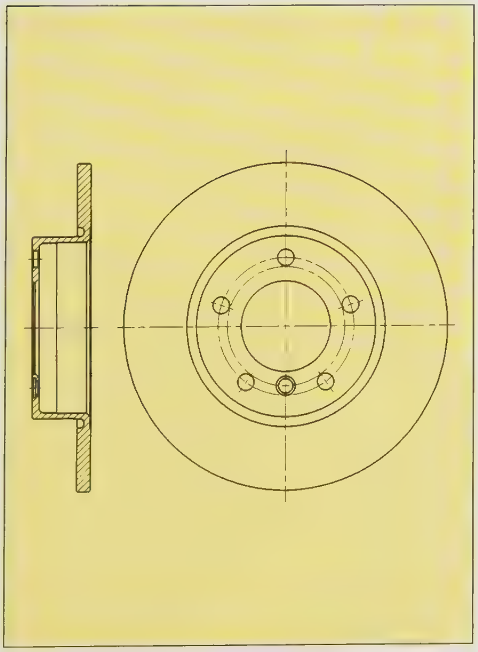
2.1.2

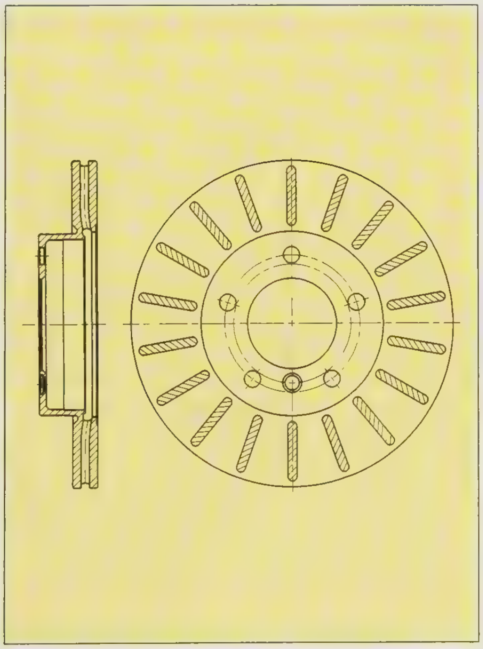


A BREMBO dual-disc caliper.

the speed. The result is that air is sucked from the central point towards the periphery; movement is created and the air moving over the surface of the disc gradually heats up which in its turn tends to increase circulation. This mechanism already exists in the case of solid discs and is sufficient when only small to medium energy levels need to be transferred, as in the case of lighter cars. As thermal energy dissipated in braking increases, the solid disc surfaces are no longer sufficient. It would be necessary, for instance, to increase the radius of the disc, but this would quickly become incompatible with the size of the wheel. It is possible to use multiple discs, as is the case on certain special or heavy vehicles, although this increases the complexity of brakes enormously. The solution adopted universally is the ventilated disc.

In reality the ventilated disc is a dual disc comprising two plates separated by metal bridges which join them together while allowing the passage of air. The

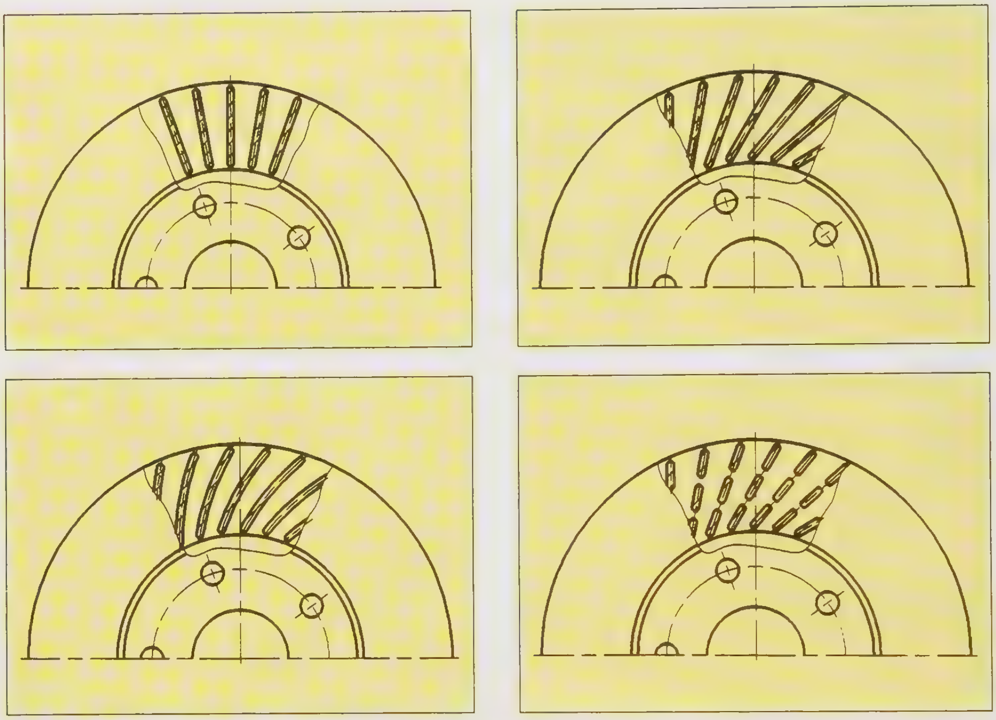




Fixed disc and ventilated disc.

2.1.2

Four blade shapes.



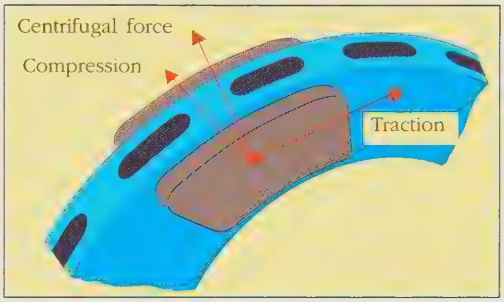
outer surfaces only are used for friction purposes. Thanks to air circulation between the plates, cooling takes place not only over the external surfaces (as with solid discs) but also over the internal surfaces. Air could enter from one side or the other relative to the carrier. For ventilation to be efficient, however, the side opposite the carrier is almost always preferred. In fact, the presence of the wheel obstructs the entry of air. Certain heavy trucks have discs where the entry of air alternates between the two sides.

Air is set in motion between the two plates and exchanges thermal energy with the surfaces of the cast iron. To a great extent this circulation depends on the form of the metal bridges, known as **blades**, as in a turbine. The shape of the blades is a compromise between efficiency and the production difficulties they create. The output of a turbine is given by the ratio between energy transmitted to the gas and the energy required to make the turbine rotate. This output improves when the blades are shaped and does not obstruct movement of the gas. This is why discs receiving a considerable quantity of energy have shaped blades which, at a given rotational speed, optimise the speed of circulation. There is, however, a limit represented by the speed of heat transfer from within the metal towards the gas. We have to bear in mind that some blades shape requires the production of both specific right and left discs.

2.1.3 MECHANICAL STRESSES

2.1.3

When the vehicle is in motion and the brakes are not applied, the disc is subjected to very little mechanical stress. There is only a traction force created by the **centrifugal** effect due to rotation of the disc. During braking the disc is subjected to two additional forces. Firstly, **compression** force as a result of the pads pressing perpendicularly against the surfaces of the disc. In turn this force is the result of the application of brake fluid pressure on the piston surfaces within the caliper. This force, very high at maximum pressure values (for example, 80 bar) creates a compression force on the cast iron to the order of a few Newton per mm^2, a very low value for this material even when hot. Instead in the case of ventilated discs, this force is only exerted on the bladed section, increasing the force tenfold at that point. This force is also exerted on the surface between the blades and can bend it - usually in an irreversible manner - if the force remains within the cast iron's elastic limit. It should be noted that the main limit to strong compression is the friction material.



Mechanical stresses exerted on a disc.

Braking action due to the pads rubbing against the disc surface is translated into a **tractive** force on the cast iron. In fact the part in contact with the pad is braked, namely is subjected to a force that opposes rotary motion, whereas the part not in contact with the pad is drawn in the direction of the disc's rotation. Even if the entire force is applied at the centre of the pad's thrust, traction force values of approximately 1-2 daN/mm^2 are obtained which are no comparison to the traction resistance of cast iron, equal to about 200 MPa, namely 20 daN/mm^2. As this force is distributed over the entire pad surface, its value is still lower and

Example of mechanical stresses to which a car brake disc is subjected

Fully loaded vehicle weight:	1560 kg
Front / rear distribution:	56%
Radius under load:	27.5 cm
Disc diameter:	238 mm
Pad surface:	35 cm^2
Car speed:	150 km/h
Braking deceleration:	0.6 g

Internal stresses in the disc:

Stress due to centrifugal force:	0.73 Newton/mm^2
Compression force per pad:	7193 Newton
Compression force:	2.05 Newton/mm^2
Braking force at centre of thrust:	7182 Newton
Traction force due to rubbing:	12.2 Newton/mm^2

remains well below the breaking point. It should be emphasised however that this limit falls with temperature and is very heavily accentuated when cracks start to appear in the cast iron. In such cases breakage can occur. The micro-cracking that may occur after long periods of use is linked to this type of repeated stress and is known as *fatigue*.

Therefore there is an ample margin between mechanical stresses applied to the disc and the limits, if reached, that could cause breakage. In order to complete the list of forces acting on the disc both flexing that can occur when braking on a bend and the dynamic stresses found when the disc vibrates must also be added.

2.1.4 THERMAL STRESSES

All energy that a vehicle loses during braking (with the clutch disengaged) is found in the form of heat generated at the disc/pad interface. The flow of heat created as braking begins is considerable; in our example it is of around one hundred kilowatts - a very high **power** indeed. By way of comparison, to have a similar electrical power level available a domestic user would need to equip the network for an intensity of 450 Amps at 220 Volts. In practice this power falls in a linear manner to zero when deceleration is constant. In spite of this, the total **energy** released by a wheel - equal to around 20 kiloJoule - would bring a little over one litre of water to boiling point in 7 seconds.

Example of heat generation in the front brake of a car

Same conditions as the previous example

Braking time:	7.05 seconds
Thermal power released at beginning of braking:	106.6 kW
Thermal energy released in 7 seconds:	377 KiloJoule, equal to 90.2 Kilo Calories

Heat is generated by contact between pad and disc surfaces. Localised temperature increases are considerable although this is by no means easy to measure. It can, however, be calculated approximately. Given the considerable temperature gradient, heat disperses in the two materials that come into contact to a degree based on their specific property in terms of this phenomenon.

Distribution of heat flows depends on the physical-chemical properties of the two materials; it remains relatively constant as far as cast irons are concerned whereas it tends to vary somewhat in the case of friction materials.

It can be seen, however, that in more than 80% of cases the heat generated ends up in the disc.

Therefore the disc needs help to cool down. This occurs as a result of air circu-

2.1.4

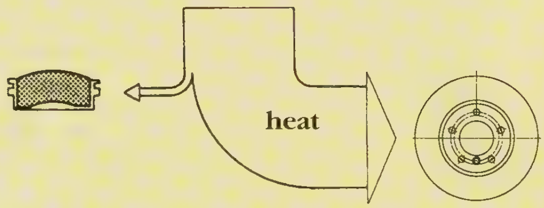
Heat distribution

For the disc

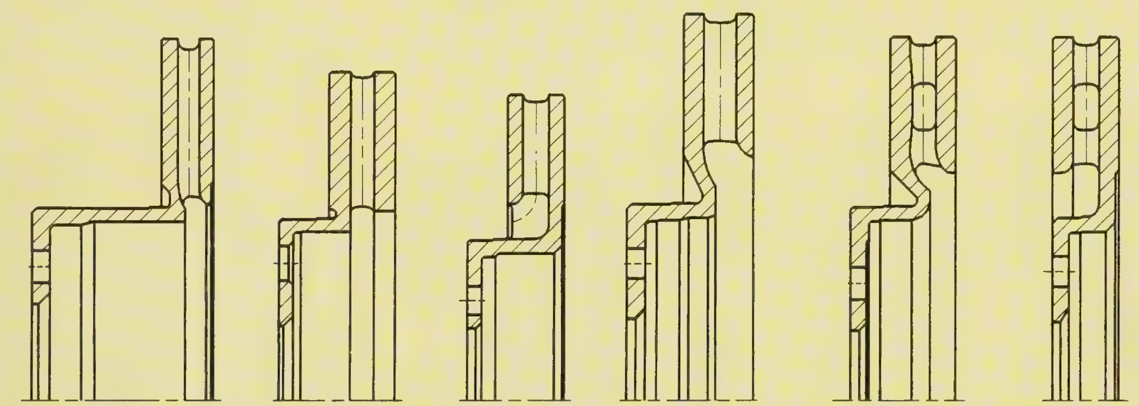
(cd) Specific heat:	500 J/kg.°K
(ρd) Specific mass:	7700 kg/m^3
(λd) Conductivity:	50 W/n.°K

For the pad material

(cp) Specific heat:	800 J/kg.°K
(ρp) Specific mass:	2700 kg/m^3
(λp) Conductivity:	2 W/m.°K



$$\frac{q_{disc}}{q_{pad}} = \sqrt{\frac{c_d \rho_d \lambda_d}{c_p \rho_p \lambda_p}} = 6{,}6$$



Different types of disc ventilation.

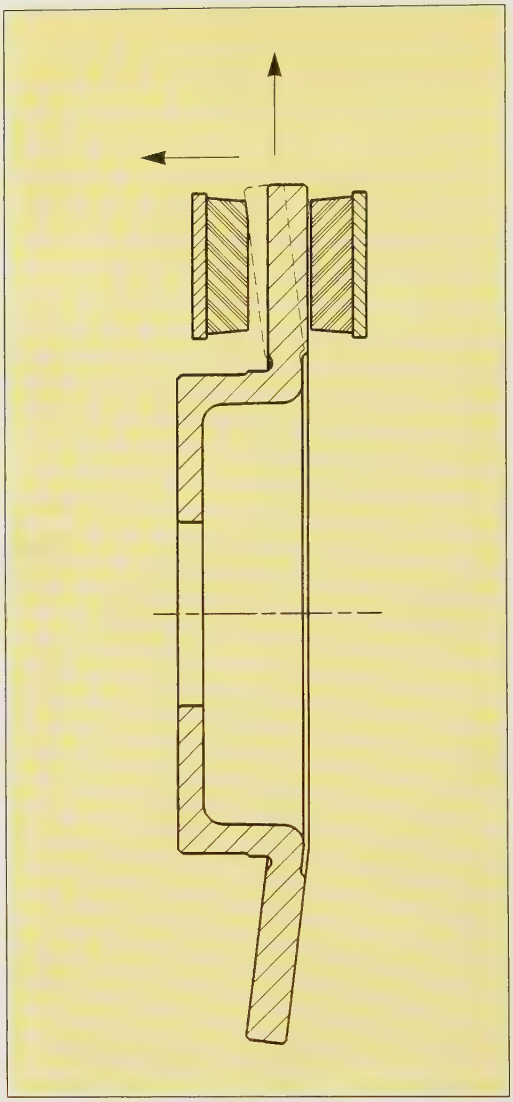
lation generated by the vehicle's motion, but above all from air movement induced by the vehicle itself. Depending on the maximum quantity of heat to be eliminated, various methods are used that in turn make the shape of the disc more or less complex. For instance the heat exchange **surface** can be increased, as in the case of ventilated discs. **Air flow** can also be increased and performance improved by shaping the blades. Entry of air through the side to which the wheel is attached is generally less efficient since the disc's environment is more confined and creates a circulation of hotter air.

An excessive temperature increase in the pads causes their material to deteriorate and also increases the temperature of the piston and, as a consequence, the brake fluid. Moreover, excessive temperature increases in the disc have numerous consequences.

The cast iron can undergo a transformation that leads to the **bluing** of the sur-

2.1.5

face (see chapter 4) or a permanent **distortion** of the disc itself. By conduction, heat is transferred towards the carrier. In this case the disc surface curves, the disc becomes conical and does not return to its original shape on cooling. Lastly, the carrier is in contact with the wheel and, as a consequence, heats the tyre.



Disc distortion due to heat.

2.1.5 MODELLING

The only way to make improvements to a physical system is first to fully understand how it functions. This is why technicians commence by taking a large number of measurements in order to form an idea of the system's reaction to the various stresses. This widely applied approach is costly and only partly effective since it is rather difficult, or often impossible, to obtain precise measurements of moving parts affected by transitory phenomena. Low cost, powerful computers have made it possible to expand such studies by modelling, also in the brake disc field.

The principle is to break down the component, in a virtual sense, into small parts which are assigned certain pertinent basic characteristics: geometry, weight, mechanical and thermal properties. Following this they are reduced to the form of simplified linear equations that describe all the possible relationships that can exist between the various elements: for example, between heat conduction and elastic properties. Of course, data representing the initial situation must be provided (for instance, the temperature map) and indications are given of the external stresses to which the element under consideration is exposed. All of these

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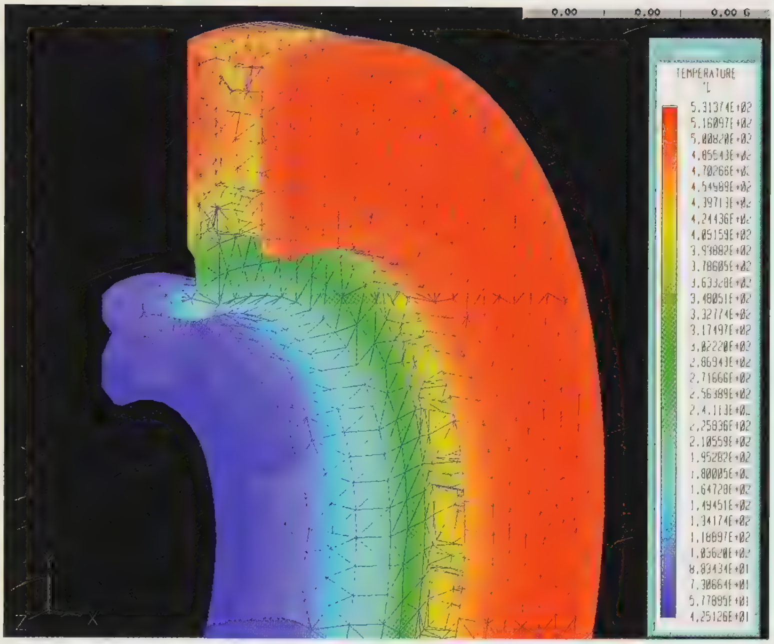
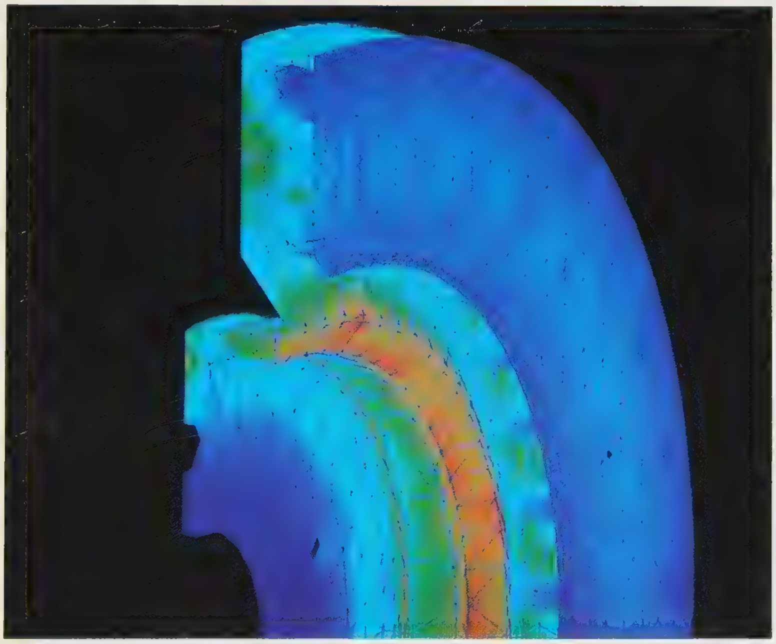
data are then processed by what is known as "finite element" software that provides new maps of the **stresses** and **flows**. After a small time increment, it is then possible to calculate the new state of the various disc elements being studied before progressing to the examination of braking itself.
The result of these calculations is presented in the form of drawings of the part concerned, where those **zones** that present the same value for a certain property (for example, all areas with the same temperature, given a tolerance margin of two degrees) are shown in a distinct colour. These maps can be processed at regular time intervals and an examination of them makes it possible to form a precise idea of subsequent transformations for a certain property within the disc. The true value of this approach is evident when, for example, a change is made to the input data relative to a geometrical detail such as a dimensional or machining modification. Such changes can be evaluated rapidly without the need to physically produce several intermediate models and then proceed with a long series of tests.



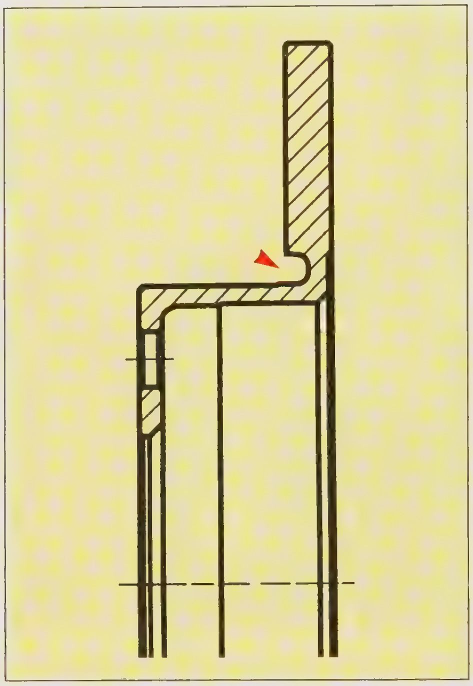
Calculation of temperature distribution in a disc. Finite element modelling.



Calculation of mechanical stress for a disc.

When calculations indicate that a change can bring about an improvement, then at that point the part is produced and multiple tests and measurements carried out.

2.1.6 IMPROVEMENTS



A disc groove.

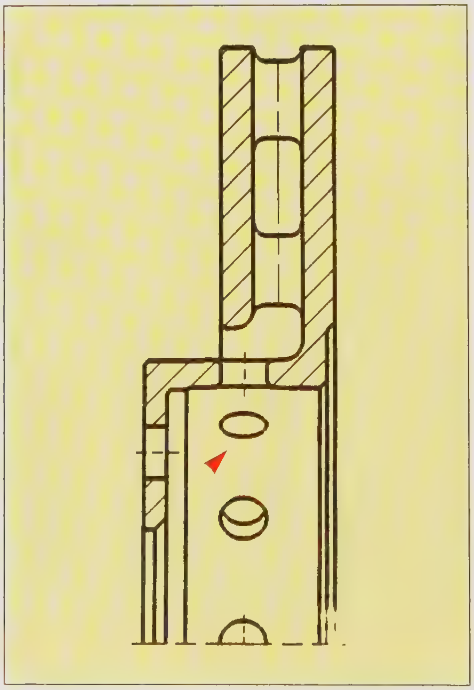


Illustration of a disc with cooling holes.

A precise analysis of shapes and stresses, optimised by calculations and measurements, has led to some to improvements with regard to which examples will be given: carrier temperature reduction, optimizing of blade design, a solution to deformation.

The wheel is normally attached to the outer side of the carrier. If the temperature of the latter is particularly high, so is the wheel temperature, with the risk that tyre rubber is subjected to excessive temperatures. Analysis of dilation also points to the possibility of a conical distortion of the braking surface. It is therefore necessary to reduce the flow of heat towards the carrier as much as possible and diminish the rigidity of the joint. This can be achieved by machining a **groove** (or channel) where the disc carrier joins the braking surface. As a result the section of this heat transmission point is reduced, the thermal gradient increases and the temperature of the carrier falls. It has also been observed that there is a clear reduction in disc distortion.

Another solution to limit overheating of the carrier is to make cooling apertures in this part of the disc. These apertures limit heat transmission from the braking surface to the carrier. The reduced mass means lower heat conduction and therefore less disc distortion.

In ventilated discs, using a different thickness for the two plates (the carrier side plate is the thicker) reduces disc distortion.

A further example of improvement is the use of blades created by means of a series of **rungs**. Compared to rigid disc manufacture, the production of blades on ventilated discs represents a complication, above all when they are shaped. They

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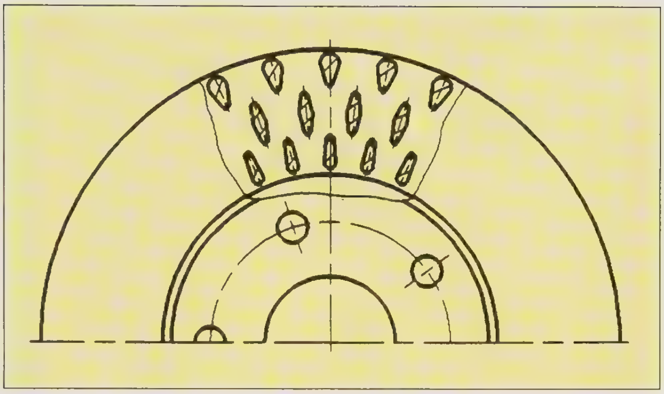
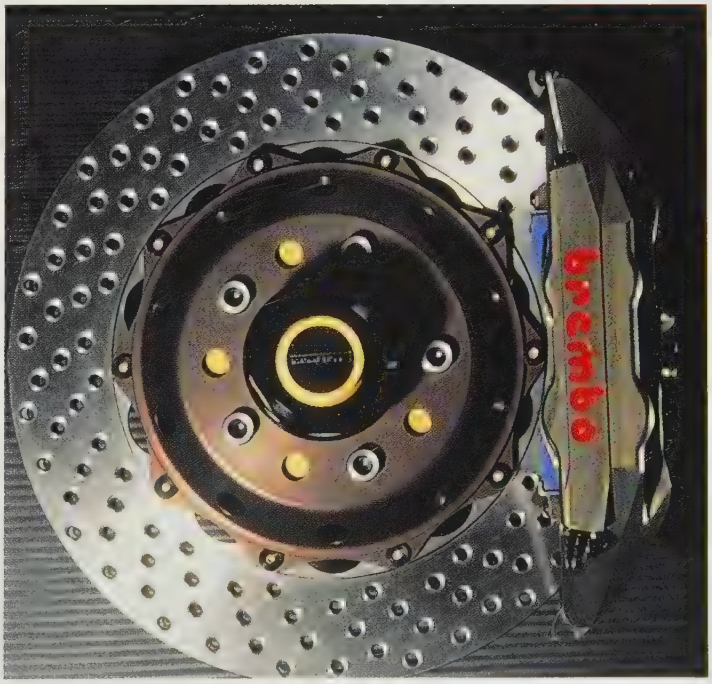
can be usefully substituted by a series of metal shaped bridges - known as rungs - and in this case the additional production complication is offset by a substantial increase in cooling and resistance of the carries to bending stress. Surface contact between the air and the cast iron is increased considerably and the greater turbulence produced improves heat exchange. This technology was developed by BREMBO in 1985.



Rung-shaped blades.

The **mixed disc**, also known as the **floating disc**, represents another innovative solution. This involves using a cast iron ring (carbon is used in F1) for the braking surfaces while the centre is made from aluminium alloy. The two parts are joined together by bushes. When in use the disc has a hot part (the braking surfaces) and a cold part (the carrier).

For particularly demanding situations, for instance in Group A rally cars, floating discs are used to overcome distortion problems. It is important for the braking surface to dilate without distorting or giving rise to stresses that could cause cracks, the first step on the way to breakage. This type of disc means that the braking sections can dilate radially, so avoiding permanent distortion and stresses. Furthermore, this technology represents an advantage both in terms of weight and wear; when worn, only one part of the disc need be replaced. Used above all on motorbikes, floating discs are also used "on the road" for other than competition purposes.



Disc with aluminium carrier.

2.2 DISC PRODUCTION

All of the steps illustrated in this section are required to produce components that ensure identical performance to brake discs offered by the manufacturers.

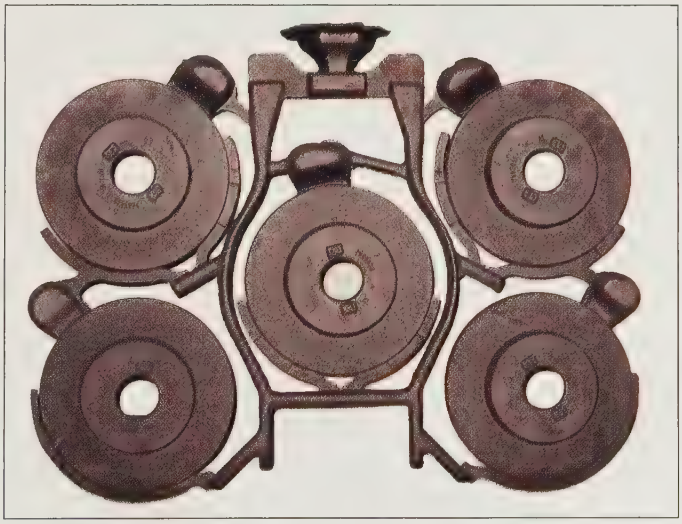
2.2.1 THE FOUNDRY

Cast iron can either be supplied to the foundry in the form of **ingots** that must then be melted down, or in liquid form, contained in thermo-isolated sacks that are easier to transport. However in modern plants the preparation of cast iron is an integral part of the production process. This preparation does not start from iron ore - ferrous products from various sources are melted down and mixed. This means that most of the cast iron needed only for tapping can be recycled and also the mix used can be prepared accurately. For example a typical cast iron used for brake discs is prepared on the basis of the following proportions:

- 30% cast iron in ingot form;
- 30% low carbon scrap metal;
- 40% recycled cast iron, namely the so-called tapping accessory.

In general, scrap produced when machining discs is not recycled in this cast iron as it contains a lot of machining oil. It is instead sent to steelworks for chemical treatment.

The load is heated in a furnace up to 1530°C so that it becomes homogeneous but also to ensure that all the scrap metal reaches melting point. For casting to take place correctly, the moulds must be filled completely and the temperature of material entering the mould must be at least 1350°C, that is well above melting point.



Bunch casting.

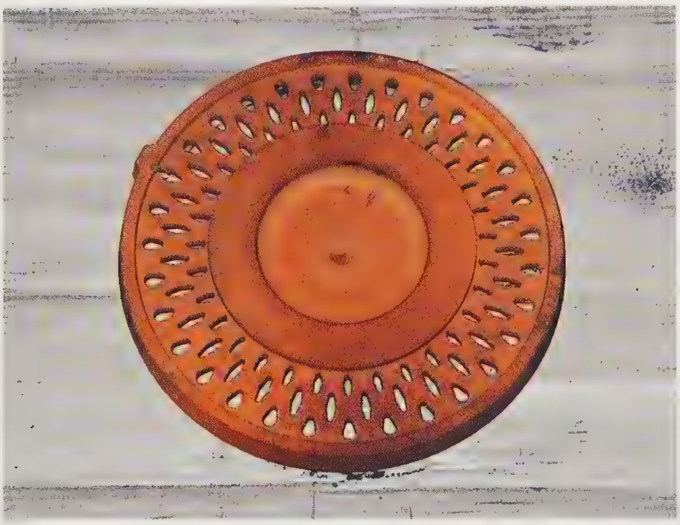
Moulds are of varying complexity depending on the item to be produced and the necessary production rhythm. All moulds, however, are designed for **bunch** casting. In fact a number of disc blanks are cast at the same time. The various cavities are joined by channels that must be of the correct dimensions to optimise distribution of the liquid cast iron. Once filled, these channels become the so-called **accessories** that are later recycled.

All moulds are made from an agglomerate of **silicon sand**. First a mixture is prepared comprising recycled sand, new sand to compensate for losses, **water** and activated clay. This mixture looks like a slightly moist, fine sand as its water con-

2.2.1

tent represents 3% of weight. **Bentonite** - namely the activated clay - acts as the bonder. A quantity of 1% of the latter is added to the new sand and, since it is not degraded by heat, it is usually recycled.

Preparation of the moulds is the most critical production stage since they can only be used once. In the case of ventilated discs, moulds have three parts: the two half-moulds corresponding to the two sides that when closed constitute the cavity and the insert, namely a negative of the blade shapes. This **insert** - also known as the **core** - is also made from sand, but the bonder used is a resin as opposed to clay, since resin gives the structure greater solidity which is required because the insert must be handled and lodged within the moulds.



Rung ventilation core.

Moulds corresponding to the two sides of the disc are produced in parallelepiped shape box-moulds filled with damp, well-levelled sand. The sand is then pressed by a steel piston, the head of which is exactly the same shape as the bunch to be cast. Preparation of the half-cavity is now complete. These half-moulds must be sufficiently solid as they have to be handled, stood on end and then turned over so as to position one half against the other. Before this operation, as appropriate, the core is inserted, centred and held in position by its outer edge. Depending on the type of production line, moulds are used either horizontally or vertically. Large-scale production plants, however, usually use vertical moulds.

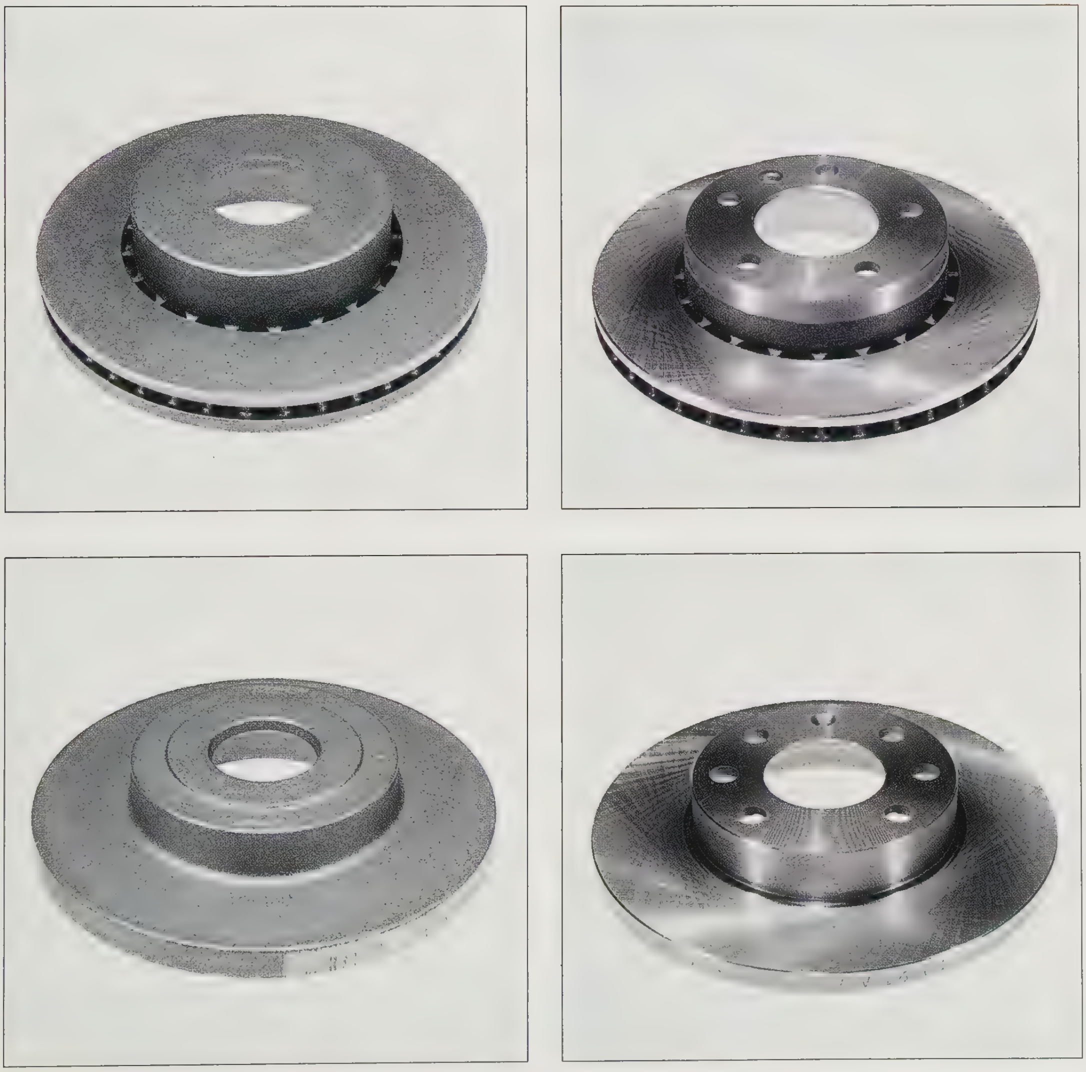
The prepared moulds move on a conveyor belt and are positioned at the tapping point. Casting takes 10 seconds for a mould with an initial temperature of about 50°C. The cast iron solidifies very rapidly and transmits its heat to the sand and water, which evaporates. The moulds move along very slowly while the cast iron cools to 500°C. When this temperature is reached the mould is opened and the sand runs out as it is once again dry. The sand is recovered for recycling while the **bunch** continues to cool. In the case of ventilated discs, the sand from the core is extracted by vibration. This sand also breaks down as the resin decomposes. As, however, it is contaminated by the products of this decomposition it is not recycled. Once the bunch has cooled it is broken up, separating the disc blanks from the accessories that will be melted down again.

At this point the blanks are much larger than finished discs. There are two reasons for this: on the one hand, machining to eliminate the more pronounced casting imperfections must be taken into account. The true technical reason, howev-

2.2.1

er, is that metal having all of the necessary homogeneous characteristics - hardness, composition and structure - is found at a certain depth below the surface. This is known as the **machining stock** concept. The additional thickness necessary is in the order of 1.5-2 mm. This means eliminating 25% of the original blank's weight.

Blank and finished discs.



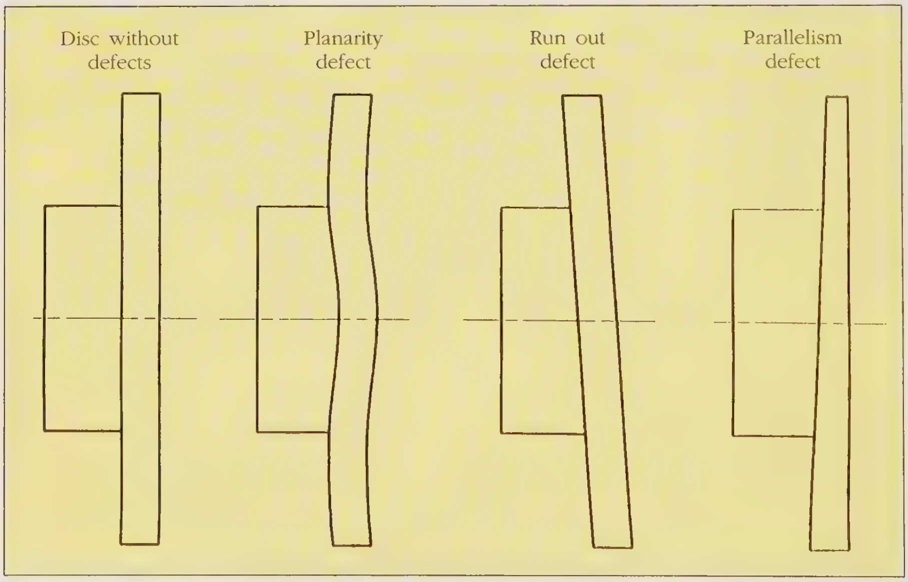
2.2.2 MACHINING

2.2.2

Lathe machining.

Blanks from the foundry already have their definitive shape, although they have a greater thickness and the "*foundry blank*" surfaces are rough, and therefore not suitable for use. The second production stage involves high precision machining. In effect this stage comprises a number of operations that must be carried out in a given order. On cars the disc's flange surface is almost always in contact with the hub. The flange is the reverse side of the carrier and must be exactly parallel to the plane of the braking surface which will be subjected to rubbing action.

The automated equipment for this machining process must be prepared and set relative to this new surface before machining of the side of the disc starts. This takes place at every stage. The equipment varies in terms of sophistication based on the complexity of machining and the production cycle. Typical high precision machines perform the task in three phases: initial roughing out, repeated machining of the carrier and braking surfaces and lastly drilling of the attachment holes. Depending on the model concerned, these sequences can be performed by more than one machine, each carrying out a different phase from roughing out to finishing.



Clearly, particular attention is paid to the **planarity**, **parallelism** and **oscillation** of the vertical, that is functional surfaces. But the machining of cylindrical surfaces also requires care. The first reason is that if the disc were to be off centre then there would be an instability that would unbalance the disc and cause vibrations. Furthermore, when the disc has been designed for fitting a *drum-in-hat* type parking brake, the internal cylinder surface of the carrier must have the same surface characteristics as the disc linings.

Particular attention must be paid to planarity, undulation and parallelism.

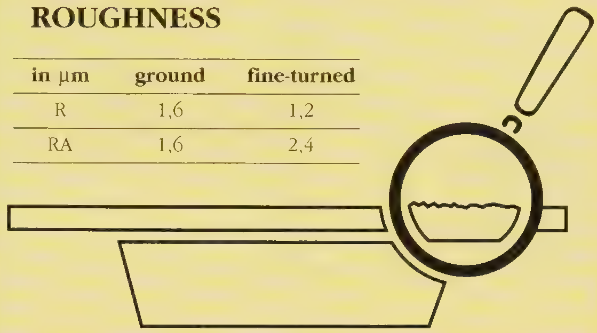
Either a **fine-turned** or **ground** final finish can be given to the braking surfaces. "Fine" machining by lathe produces a concentric groove. Measured on the

basis of a disc's radius, roughness is believed to be important by those in favour of a ground finish. Using modern machinery, circular roughness, at either the top or the bottom of a groove, is very low. On the contrary, a ground surface presents a circular and **radial roughness** similar to the **circular roughness** of a fine-turned disc.

The choice to use grinding can be dictated by two aims: to avoid the groove that tends to dislodge pads from their seats and to accelerate running in of new disc-pads. The grinding operation requires higher skill levels as it could cause a loss of tolerance relative to *oscillation*.

ROUGHNESS

in µm	ground	fine-turned
R	1,6	1,2
RA	1,6	2,4



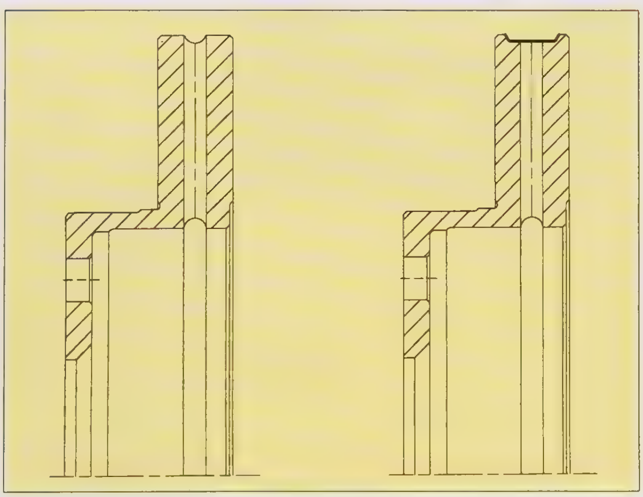
Roughness of ground and fine-turned discs.

Finishing of disc braking surfaces (ground or turned finish) depends on the decision of the Car Manufacturer's Development Centre and Technical Department that specified the charateristics of the disc.

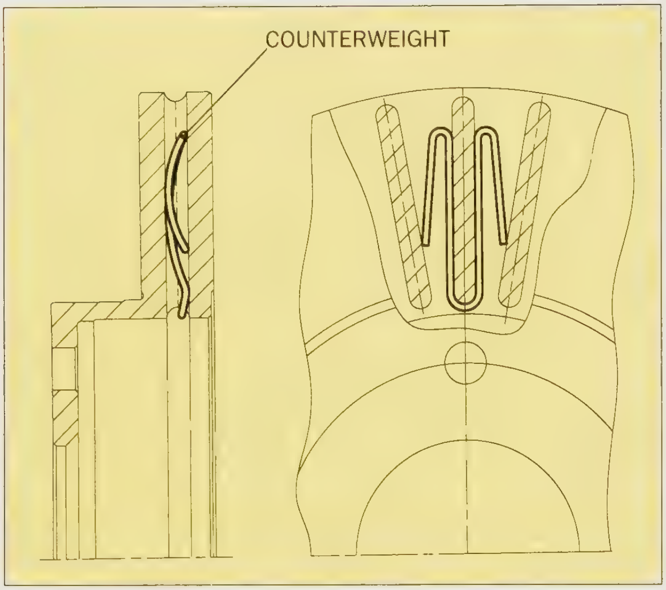
Equipment for measuring dimensions.

In spite of casting and machining quality, a slight imbalance in terms of weight distribution may persist. This is why ventilated discs are automatically and systematically **balanced** by removing stock. This is performed by milling. The machine automatically rotates the disc, measures the imbalance and determines the direction around which the disc would rotate if it were suspended by a thread running from its centre. Machining is performed parallel to this direction. The milling machine eliminates material around the outside edge of the disc, passes continuing until the disc is perfectly balanced. The balancing of 90% of discs only requires machining that involves a subtended angle of less than 35°. Milling can extend over an arc of up to one quarter of the circumference.

Another way of balancing a disc is to insert



Balancing section.

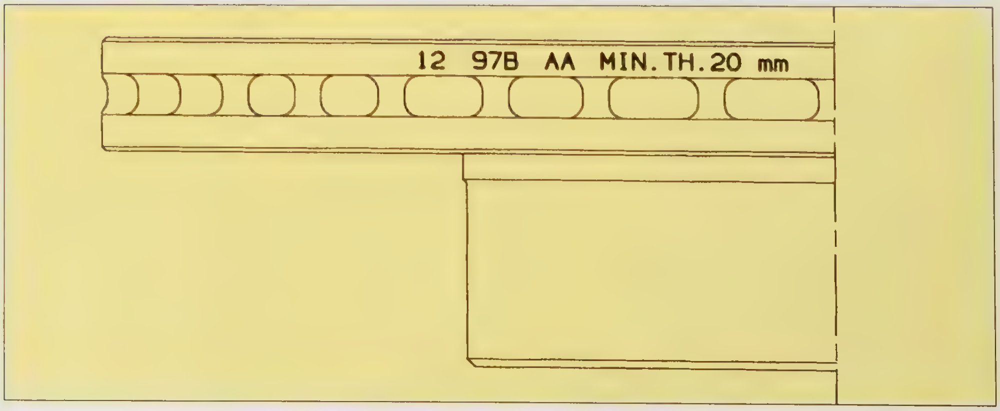


Balancing springs and positioning.

springs in the blading; these must never be removed either during assembly or maintenance operations.

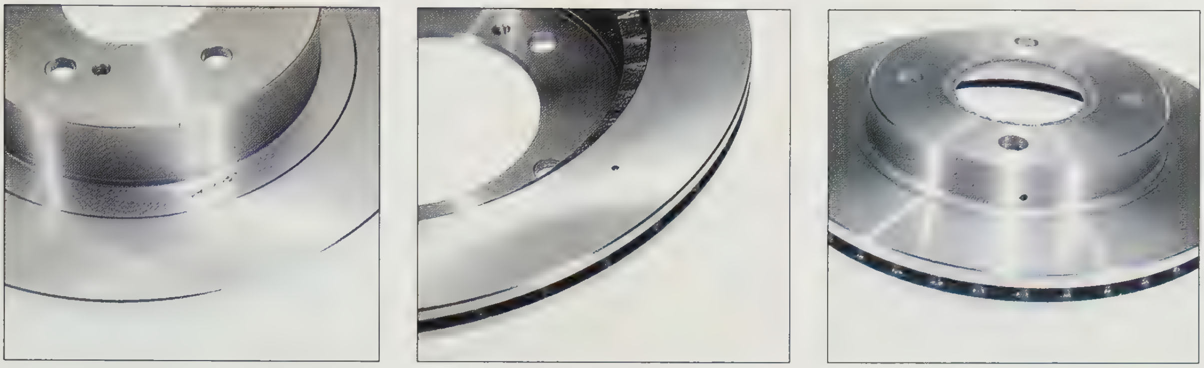
All discs are marked by means of **incision** on the surface of the external border. Among the indications given are the casting and machining batch numbers and also the minimum thickness below which a worn disc must be replaced. Discs are immersed in a special oil to protect them from oxidation during storage. However, this oily film must be eliminated using a solvent before fitting the disc to a car. Final **packaging** of discs follows one very precise rule: the pack must contain a pair of discs from the same **batch**. In fact discs to be fitted on the same axle must come from the same production batch without fail.

To ensure balanced braking it is necessary to install a pair of discs from the same batch.



2.2.3 QUALITY CONTROL

2.2.3



Metal rarefaction and porosity.

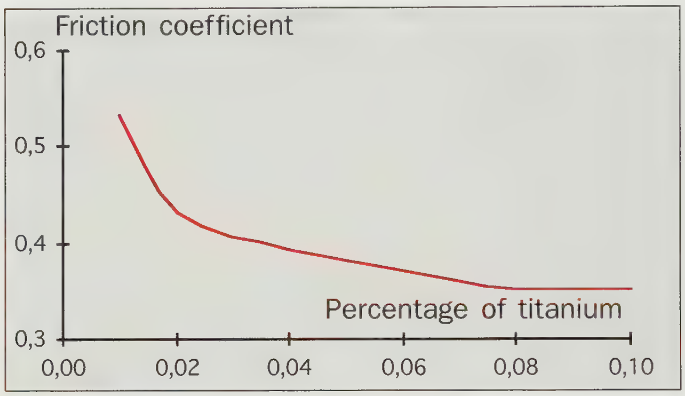
It is important - and extremely difficult - to produce discs to the same tolerance criteria throughout the year, in order to ensure the same performance level for all of them. This is why all production is subject to statistical process control (SPC). During the various production stages automatic measurements are taken on a sample of items. This enables adjustments to be made to machinery but also signals if, from a size or weight standpoint, variations from standard values are too great or too frequent. At the end of production all discs must pass a visual check. This means that discs can be discarded if the machined surfaces show visible defects due to casting conditions (for example, metal rarefaction or porosity). Such pieces are discarded and their cast iron recycled. Lastly, checks can be carried out on all pieces produced in the workshop, usually when the car manufacturer has made a specific request in this sense.
Other measurements, like checking the surface state for example, are performed in the laboratory on a sample. Certain absolutely essential tests are destructive and can therefore only be performed on samples although the low number of items examined does not change the discard rate significantly. In fact, just as it is

SPC measurement bench.

2.2.3

not possible to test the quality of matches by lighting each one of them, it can however be shown that a properly evaluated statistical check is sufficient to guarantee that, if necessary, all of the matches will light.

Chemical analysis of the cast iron is already carried out by the supplier but even so it is repeated by the disc manufacturer. The most appropriate analytical method is to use **emission spectrometry** or spark spectrometry. As the name implies, a brief but high current is applied to create a spark between the conducting electrode and the disc. Taking into account the distance and size of the electrode - the surface examined is a circle about 4 mm in diameter - sparks are created at a number of points in order to obtain a representative measurement. The effect of the heat generated and the localised temperature causes the metals contained to volatilise in a plasma. They then emit a light, the wavelength of which corresponds to their atomic structure whereas the intensity is proportional to their concentration. The precision analysis of the light spectrum emitted indicates the formula of the cast iron and the result obtained can be compared with the reference formula. Two elements in particular cannot be analysed accurately using this method - carbon and sulphur - and so they are analysed by more conventional chemical procedures.



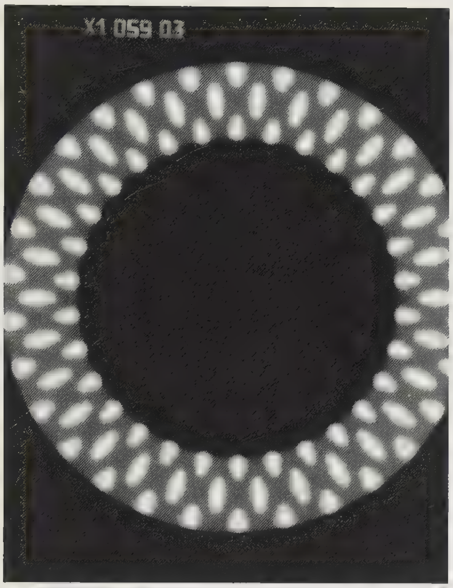
Effect of titanium concentration on friction coefficient for cast iron.

Emission spectrometer.

Physical measurements are taken both on finished items and on test samples. **Hardness** is measured on the Brinell scale. The punch is spherical with a diameter of 10 mm and a force of 3000 kg is ap-

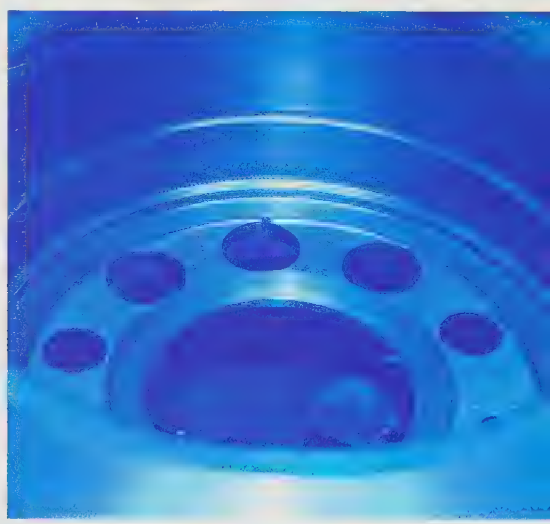
Hardness measurement equipment (Durometer).

2.2.3



X-ray of a brake disc.

plied when measuring blanks, or alternatively a diameter of 2.5 mm and a force of 187.5 kg is used for finished discs.
Penetration of the sphere is measured and a cross reference table provides the hardness value. The Vickers micro-hardness method is hardly ever used with cast iron plates as the punch is too small and there is the risk of measuring the hardness of graphite plates or the surrounding perlite.
Traction resistance can only be measured on cut pieces, using conventional traction equipment.
At the end of the manufacturing process, we have seen that all discs are checked visually although naturally such a check cannot reveal possible internal defects. In fact there can be internal cracks, namely internal breakage, or bubbles due to gas trapped during casting. **X-rays** make it possible to check the integrity of the material, namely the absence of discontinuity. A high-power X-ray tube is positioned horizontally above the disc and the sensitive film is placed below it. The negative is then examined and the shape of the blades and any possible defects observed. This is a non-destructive analysis.
X-ray radiography does not reveal extremely small cracks or those perpendicular to the disc surface. A **metalloscope** is used to test for the presence of such defects. Everyone will remember the experiment where iron filings are placed on a sheet of paper and are oriented by positioning a magnet under the sheet.
Metalloscopic analysis, while rather more complicated, is similar to this experiment. The disc in horizontal position is subjected to an intense magnetic field created by two coils located either side of it. Two contacts pass a continuous electric current through the disc. The surface of the disc is covered by a thin film of magnetic powder that is

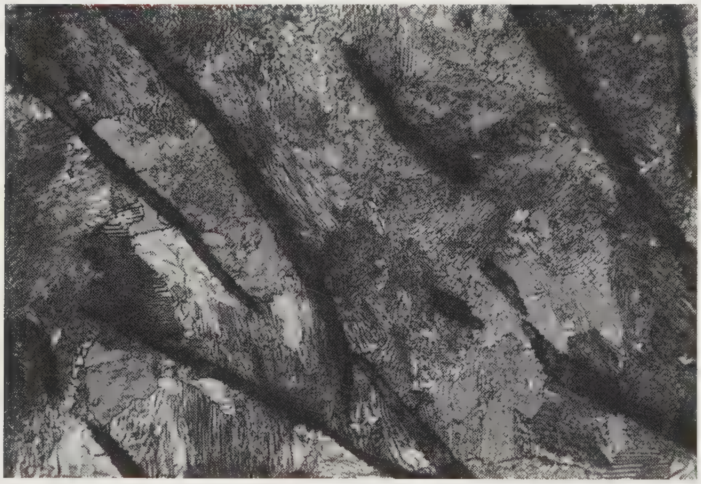


The metalloscope highlights cracks.

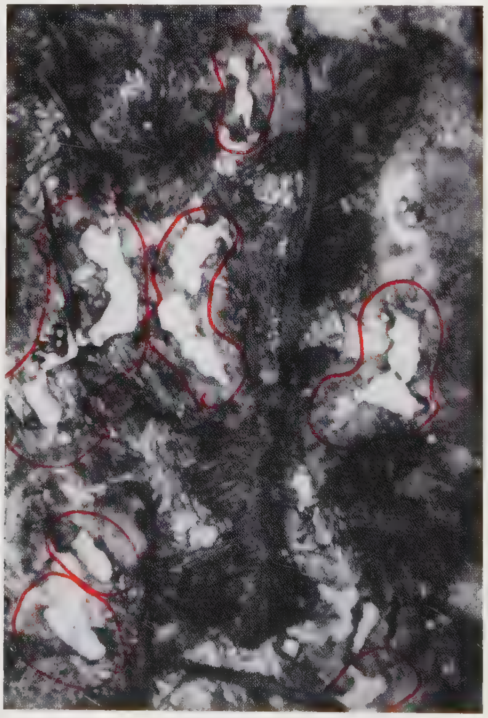
2.2.3

oriented in the direction of the field. If there is a crack, it creates a disturbance which becomes visible because of change in the orientation of the powder, an effect that can be seen more clearly when the disc is slowly rotated. Again this analysis is non-destructive. It is clear that the quality of the cast iron is of great importance in terms of disc performance and quality. The same may be said for the metallographic **structure** which is not only the result of composition but also of thermal processes. This is why certain discs are systematically taken and cut in order to perform a **metallographic analysis**. The sample is first polished then the surface is treated with a corrosive compound (Nital) that strengthens the contrast effect. The analysis can either be performed directly using the microscope or by means of photographic reproduction. Computer image analysis is a modern method that allows the various elements comprising the surface - graphite, perlite, inclusions, etc. - to be easily and accurately quantified.
In particular a check is run for excessive quantities of ferrite, cementite and manganese sulphate, each of which must occupy less than 1% of the surface.

Specification grey cast iron. x500 magnification.



Non-specification grey cast iron: contains too much ferrite. x500 magnification.



2.3 TESTING

As for all car components, the most reliable tests for discs are those carried out directly on the vehicle for which they were developed. However, such tests present two drawbacks. On the one hand, tests on vehicles only provide overall results since the testing involves the whole brake and also the environment in which it operates. On the other hand, the cost is very high in as much as such tests cannot be automated - a technician must always be at the wheel. This is why technicians have developed laboratory test instruments that enable them to focus attention on one particular performance aspect. This solution means that vehicle tests are freed from a certain number of constraints, enabling greater emphasis to be placed on the user-braking relationship.

2.3.1 TESTING INSTRUMENTS

2.3.1.1 IN THE LABORATORY

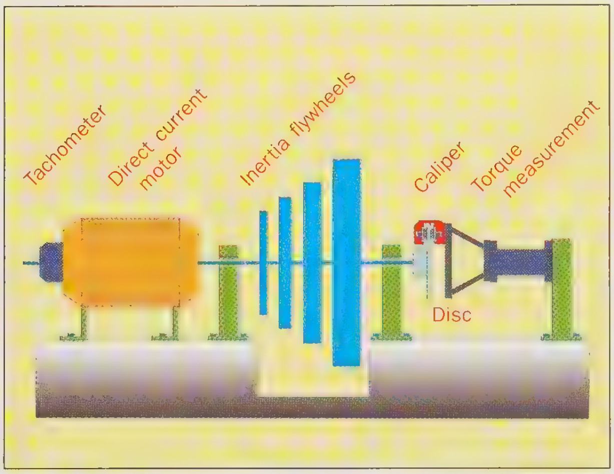
The more frequently used and most widespread instrument in the brake sector is the **dynanometric bench**. As the word tells us, this is a piece of equipment capable of measuring forces, therefore also those involved in braking. There are several sizes and types of dynamometer. Here we will only describe the up-to-date model that permits testing of the entire brake and its surrounding environment and can simulate the braking of a vehicle, or more correctly, that of a wheel.
First and foremost an inertia dynamometer comprises an **electric motor** capable of controlling a variable speed inertia flywheel and, more specifically, the speed of rotation corresponding to the maximum speed of the vehicle for which the brakes are to be tested. The power output of the motor need only be in line with that of the vehicle's engine if the intention is to make a real-time simulation of a series of braking actions taking place in a very short space of time. In this case it is necessary to communicate a kinetic energy to the inertia masses which is identical to that supplied by the engine to the part of the vehicle affected by the brake being tested. The **inertia masses** are the flywheels fixed to

> Bearing in mind that the inertia of a disc rotating around its own axis is:
>
> $$I_{kg \cdot m^2} = \frac{MR^2}{2}$$
>
> where M is the mass and R the radius.
>
> Going back to the example of the car weighing **1200 kg** and travelling at **120 km/h**. If the braking load on the front wheels is 60%, to come to a complete halt the brake must dissipate:
>
> $$E_C = 199\,960 \text{ Joule}$$
>
> To store this energy in a dynamometer will require an inertia equal to:
>
> $$I = 31{,}3 \text{ kg m}^2$$
>
> If a single inertia flywheel were to be used, it would need, for example:
>
> **Diameter = 1 m**
> **Mass = 250 kg**
>
> If the dynamometer doesn't have this mass then a number of flywheels will need to be combined to obtain the nearest possible inertia.

2.3.1.1

the crankshaft. Normally a number of flywheels with different inertia are available so that it is possible to select those that accurately produce the desired total inertia. The **disc** and possibly the wheel are fitted at the end of the shaft. The **caliper** is attached to the bench, often with the aid of the axle of the vehicle being tested.

Diagram showing the principle of a dynamometer bench.



A torque measurer is placed between the caliper and the fixed part of the dynamometer bench in order to quantify the force exerted on the caliper, a force that tends to cause it to rotate when the disc is braked. Modern dynamometers use computer-controlled **automatic devices**.

A **test procedure** comprises a series of braking actions performed at various speeds, temperatures and, for instance, pressures. Certain procedures are intended to be representative of the average user when braking while others aim to evaluate the consequences of extreme braking action during which the discs reach temperatures that generate an easily observed red hot colour. Programming a braking action requires a certain number of typical stages.

Firstly, as previous braking has heated up the disc, there is a pause until the temperature falls to a pre-established value. To achieve this the disc is rotated at a speed sufficient to ensure effective ventilation and is usually the longest stage of the test. Once the desired temperature is reached, the rotation of the shaft is regulated to correspond to the vehicle's travelling speed, expressed in km/h. At this point the motor is disengaged, for example by cutting off the current, and braking takes place.

Laboratory thermal shock test.

Braking is carried out by increasing the hydraulic pressure in the circuit. Two types of braking action are normally used: with a **constant pressure** or with a **controlled torque**. In the latter case, after applying pressure, the torque is measured and as soon as the desired value is reached, the pressure is then regulated so that the torque remains at the established level (it can be constant or vary according to a predetermined cycle). This method is reliable in as much as it

corresponds to a constant deceleration that is very similar to a driver's braking action.
Throughout the braking procedure the automatic device records the values and trends of various parameters: speed, temperature, pressure and torque. Using these values it is possible to calculate the distance travelled and the friction coefficient at every possible moment. According to requirements other measurements are taken: for instance, the temperature at various points throughout the disc, the temperature of the pads, disc distortion, the amount of liquid introduced into the caliper or the frequency of vibrations.

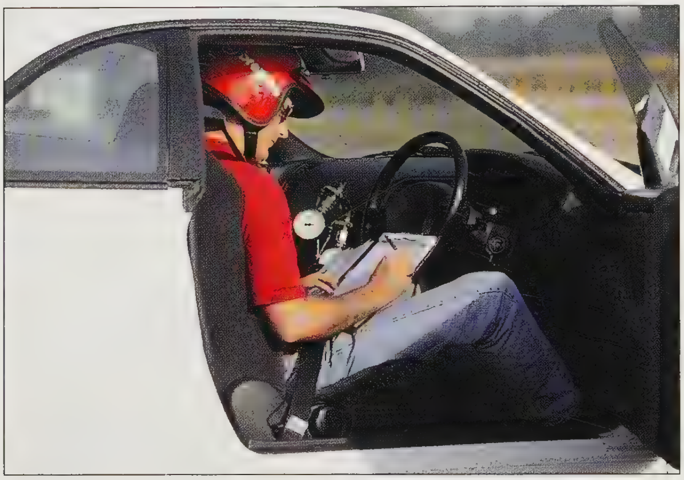
2.3.1.2 ON THE VEHICLE

As mentioned, the majority of test procedures can be conducted using a dynamometer. However, such tests are only rarely able to reproduce the exact environment within which the item tested must perform. This is why the final procedures to obtain homologation are always carried out on the vehicle itself. In fact the vehicle brings stresses into play that are almost impossible to reproduce in the laboratory. Among these are transfers of mass and efficiency between the front and rear sections, the environment (temperature), mechanical stresses, deformity caused by contact with the ground and the effect of vibrations that are not produced by the brake itself. In addition, vehicle tests make it possible to highlight specific instances of wear due to the type of route and the brake's sensitivity to water. Although they are not really tests on brake components, ABS and ASR tests are also carried out on vehicles.

Test vehicle.

In order to perform braking tests, certain modifications must be made to the vehicle. However, first and foremost the **vehicle** must be available for testing and this is not always possible. For instance this may be the case during the development stage when the vehicle does not yet exist or when it cannot leave the manufacturer's plant for reasons of secrecy. In such cases the **brake** to be tested is fitted to a similar vehicle in terms of weight and concept: this is often a prototype equipped with the definitive suspension and wheel assembly. The **brake fluid circuit** is modified by fitting solenoids so that either only the front or the rear brake is activated. Braking action is then controlled by hand, where-

as for safety reasons using the pedal to brake overrides the manual control and acts on all four brakes. The tests sometimes include sharp braking, at the limit of wheel grip. In such cases the ABS action is excluded.



Interior of a test vehicle.

As the prime objective of tests is to carry out measurements, the vehicle is fitted with instruments that enable reliable and accurate results to be obtained. The disc surface **temperature** is measured with the aid of thermocouples that either rub against it or are inserted in holes in the braking surface created for this purpose. Fluid **pressure** values are converted to an electrical current measurement by means of a transducer. The vehicle's **speed** and the **distance travelled** during braking can be obtained from the on-board instruments available (speedometer and odometer). It is accepted that these values are not precise as they count wheel turns and do not take into account tyre slip against the road surface. If a higher level of accuracy is required then a *fifth wheel* - similar to a bicycle wheel - can be fitted to the vehicle and given the fact that it bears no weight it is not subject to slip. **Deceleration** can be calculated using the previous data, although the use of an inertia mass accelerometer is usually preferred. This equipment creates an electrical signal proportional to acceleration or deceleration and a device governed by the on-board computer is used to record these data. In addition to data **acquisition** and **storage**, this device is used to give sequential indications to the driver as to the type of braking action to be performed. A method that is particularly useful when long and complicated procedures are involved.

2.3.2 LABORATORY TEST PROCEDURES

These tests are performed when, for various reasons, either an expert opinion is required or - and this is the more frequent case - during development of a disc for a new use. A complete report includes at least ten tests, each of which refers to a specific property of the disc. In the majority of cases the same test procedure brings a number of properties into play. Results need to be cross-referenced for evaluating properties separately.

Certain tests aim to evaluate disc **performance** during the braking process. Such tests must be conducted extremely carefully as a variation in pad composition

2.3.2

and structure produces a greater effect than modifications to a disc. This is why it is important to have a standard for pads, so that comparisons can be made between discs. These pads must also be rigorously checked (sensitivity to speed, to pressure and to temperature).

In this manner it is possible to establish differences in friction efficiency based on the composition of discs and the state of their surfaces. Disc ventilation is a factor that seriously affects temperature and, as a consequence, friction. Comparison of temperatures reached by different discs during testing conducted in a perfectly identical manner provides useful information on cooling efficiency. As the friction coefficient is temperature-sensitive, this effect will emerge from the braking results. Three types of such dynamometer tests exist. Procedures based directly on *European testing regulations* are too general to be able to extract precise information at disc level. A *European group* of brake producers and manufacturers have developed a series of procedures known as EUROSPEC Ak_n. The purpose of these procedures is to assemble the various companies' numerous protocols, that comprise both performance surveys at several temperature levels (AK1) and detailed measurements of brake efficiency before and after damping at high temperature (AK2). These tests still remain at a very general level as they measure the efficiency of a group of components: caliper, pads and disc. Specifically, they envisage measurement of the quantity of fluid forced into the caliper, a fact that depends on the distortion of the caliper and pads but does not concern the disc. Lastly each company has its *own* tests that often come to represent their historical standard and benchmark.

Nine laboratory test procedures to determine a brake disc's characteristics

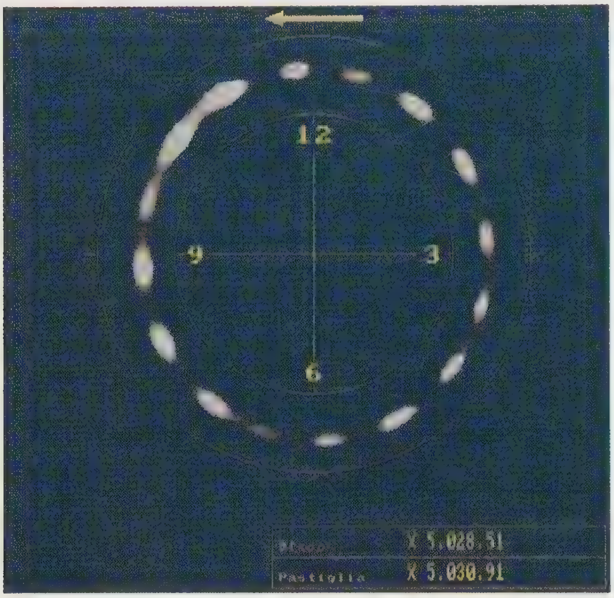
Procedures	Proposed purpose
Thermal shock Thermal fatigue	Evaluate a disc's resistance to thermal cracking on the braking surfaces.
Mechanical stresses	Evaluate the mechanical resistance of the connection between the carrier and braking surfaces, paying particular attention to circumferential cracks.
Distortions	Evaluate thermal inertia to heating and cooling properties Measure temporary and permanent distortion.
Vibrations	Evaluate the onset of vibrations in the complete braking system during the slowing down phase.
Judder	Evaluate possibilities of judder developing in the combined disc/pad unit. Visualise - using an infrared ray telecamera - temperature distribution over the braking surfaces.
Wear	Measure disc and pad wear. Measure thickness and weight variations, also measure DTV.
AK_1 and AK_2	Complete dynamometric measurements of the combined disc/pad braking performance.

The second aspect of laboratory tests concerns the evaluation of **mechanical stability**. Measurements can be carried out either during a dedicated procedure or during performance evaluation procedures. Such tests consist of taking geometrical measurements during functioning, when hot and turning. These are therefore easier to perform on a bench in the laboratory than on a vehicle. Distortion, undulation, DTV and other measurements are carried out with the aid of

2.3.3

capacitative transducers that permit measurement relative to a contact-less reference plane.

Measurements of **wear** are only performed from time to time as this is a slow process. In fact not only does the disc have to be disassembled but also the pads, in order to make a complete survey of thickness and weight reductions. These measurements are taken after the standard procedures mentioned previously although they only give approximate results as a true test procedure for wear must reproduce use and is therefore, by necessity, long-drawn-out. Increasing the speed of wear, obtained by making test conditions more severe (heavier braking action, higher temperatures), does not always provide very realistic results.



Infrared ray thermograph of a tested disc.

"**Extreme**" tests are, on the other hand, effectively based on this approach (thermal resistance). Their aim is to destroy the disc by subjecting it to extreme conditions that cause it to degrade. Attempts are above all made to create cracks and even breakage in order to learn the limits that must not be exceeded and therefore are of help in sizing the disc correctly. To achieve this the disc is subjected to rapid, repeated thermal shock where the aim is to create localised thermal stress. During such tests temperature measurements can be taken at various points on the disc's surface in order to highlight the correlation between high temperature points and the location of cracks. As will be seen later, it is also possible to perform laboratory tests to identify and analyse the onset of **noises** and **vibrations**.

2.3.3 ROAD TEST PROCEDURES

Once the vehicle is ready only two technical issues need to be resolved. First of all, the **load**. In fact many tests envisage a full load. There is a very convenient method for loading the test vehicle. This entails filling water tanks secured to the rear seats by which means the weight can be regulated precisely. The second issue concerns the test circuit. Certain tests can only be carried out on a private **circuit**, with no members of the public present for safety reasons (for instance, in the case of high speed tests). Instead many other tests can be performed on the open **road** provided the vehicle has been properly registered and the tests concerned do not involve breaking the Highway Code. Such tests must be con-

ducted by brake technicians. The peculiarity of tests carried out on a vehicle is that braking torque cannot be easily measured and therefore it is not possible to calculate the friction coefficient.

In the majority of cases it is deemed sufficient to express the results in terms of braking distance and deceleration or, better still, by means of the **deceleration/pressure** ratio. For a given brake this ratio is proportional to μ if the mass remains constant, a circumstance that does not hold true when a high load transfer is involved.

Test circuit vehicle.

While **European regulations** (annex 12) establish that certain homologation tests can be conducted using a dynamometer, almost all of them take place on the road. Such homologation tests are more useful in the case of heavy trucks. In the case of cars they only provide information on safety and are rather deficient as far as a precise description of brake performance is concerned, an aspect which is instead required for disc development and by the manufacturer. We should bear in mind that the two main tests are *type 0*, in which braking distance is measured for cold brakes at various speeds, and *type 1*, that measures the same parameter but after the brakes have been warmed up.

2.3.3.1

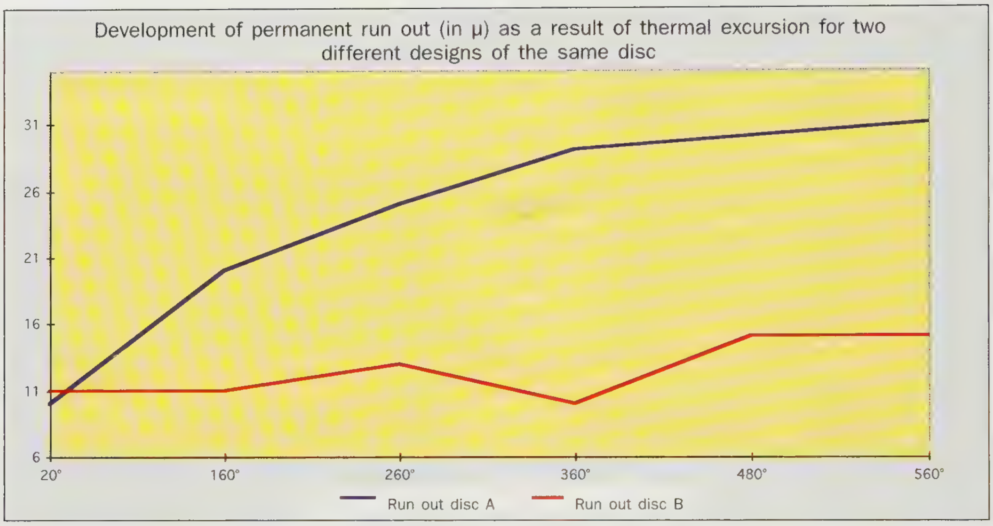
2.3.3.1 BRAKING CHARACTERISTICS

Performance measurements are carried out on a circuit using one of several methods, depending on the manufacturer's requirements. Once more to a large degree such tests involve analysis of the values for three parameters: speed, pressure and temperature. Procedures usually include one or two warm-ups with measurements to determine at which point braking performance is restored as the temperature falls again. Even though these tests involve the brake as a whole they can provide specific information about the disc. For a certain technology and given disc thickness, temperature analysis provides data on ventilation when the disc itself is attached to the wheel. Wear can be measured at the end of the test although after thermal exposure checks are above all made for possible distortion.

Tests to measure **wear** are rarely performed on the road as they are so time-

2.3.3.2

Characteristic result.

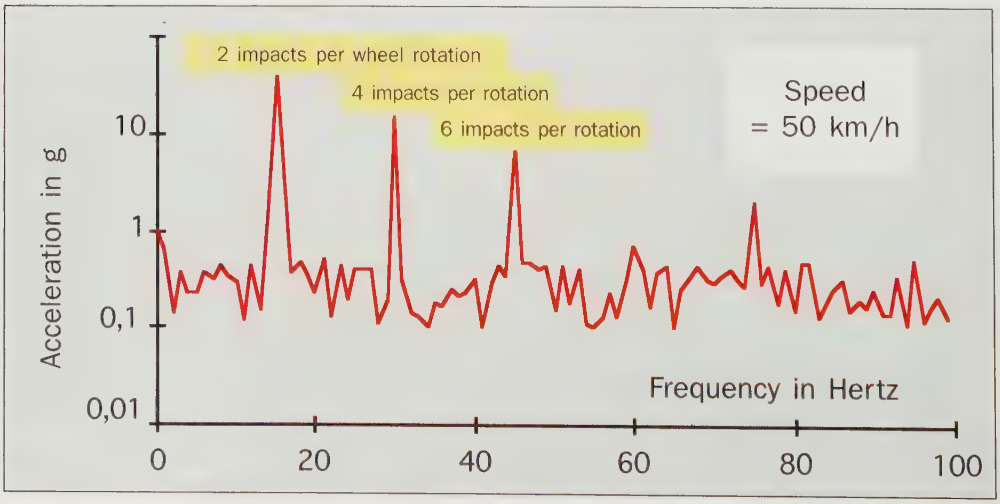


consuming. Instead thermal shock testing is currently used in order to determine the limit beyond which **cracking** may take place.

2.3.3.2 STUDY OF VIBRATIONS

One of the truly interesting aspects of vehicle testing is the analysis of vibrations and noise. In fact in this particular area of braking performance only tests conducted on vehicles are really significant. A braking system (caliper, disc and pads) may produce noise (its own vibrations) when used on a certain car but instead not give rise to this phenomenon on another model. We might also note that possibly only certain units of a model are subject to vibrations. From this it can be deduced that problems which may appear to be of a design nature are

Vibrations.



2.3.3.2

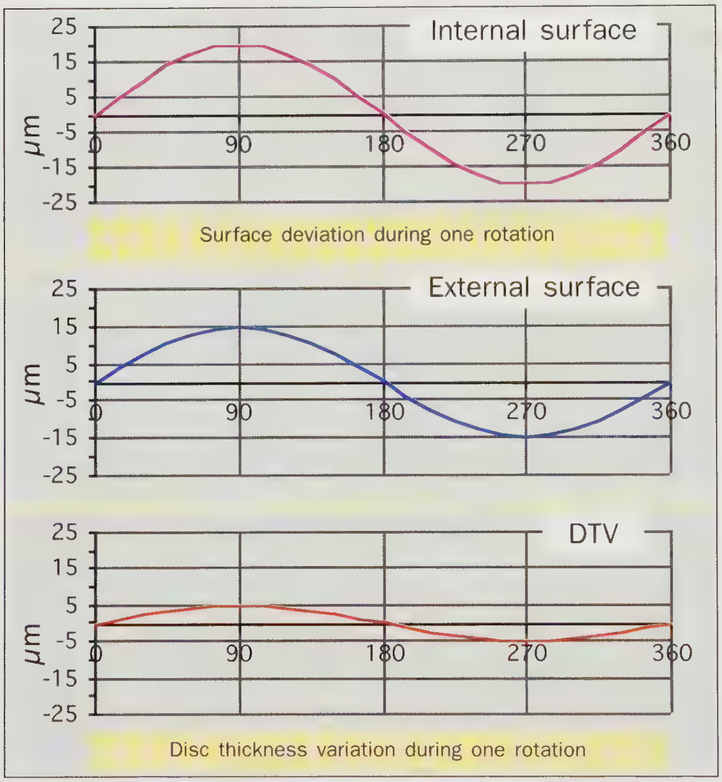
not in reality only the result of the actuator system or peripheral components (suspensions, tyres, hub, etc.), but of conditions of use (climate, route, type, load, user, etc.).
From the theoretical standpoint there is not much difference between vibrations and noises since the latter are produced by their own vibrations that cause the surrounding air to move at a sufficiently high frequency to be audible to the human ear. Even so we will deal with the two phenomena separately as the causes and methods by which vibrations and noises are generated are very different. As far as braking noise is concerned, this will be covered in a later chapter.
By the term **vibrations** we mean movements of parts of the vehicle that are felt, as opposed to heard, by the driver, even though certain vibrations are accompanied by noise. The majority of these vibrations are perceived at either the brake pedal or steering wheel level. In simple terms it can be stated that vibrations are essentially due to a succession of impacts between disc and pads. Consequently it is understandable that the frequency of such vibrations is linked to the wheel's speed of rotation and, therefore, that this frequency gradually diminishes with braking, that is, as speed drops. These vibrations are also said to be **synchronous**. The frequency varies from around one hundred or more Hertz when braking at 130 km/h on the motorway to almost zero when the car has almost come to a halt. If there were one rough patch on the disc then there would only be one impact for each turn of the wheel. Normally however, there are at least two such patches. For example, if we take the case of a badly installed disc that is not parallel to the hub, the first impact will involve the left pad and then, half a turn later, the right pad. In many cases where vibrations are present there are more than two impacts for each turn of the wheel.
In an attempt to better describe vibrations, they are classified on the basis of how they are generated as opposed to their effect. Two large groups of vibrations can be identified: **Cold Judder**, linked to dimensional anomalies independent of use of the brakes (anomalies that often occur when the brakes are not used) and **Hot Judder** that occurs after use at high temperature. Cold judder vibrations are due to both geometrical imperfections of the disc itself and to defects caused by installation and excessive play (for instance, in the bearings) and, as a general rule, to anything that may increase disc wobble. This wobbling causes irregular disc and pad wear. Cold judder is a vibration caused typically by wear when the brakes are not in use (long journeys on the motorway). These cold judder vibrations are noticeable during deceleration and at low to medium pressures, situations that occur frequently when slowing down slightly on the motorway. Such vibrations have a high frequency and their effect is even more unpleasant when travelling at high speed. If the disc is really the cause of such vibration this is due to a production defect: a substantial variation in parallelism

2.3.3.2

known as **DTV** (Disc Thickness Variation) or a wobble or planarity defect which in turn causes a DTV. Instances of this occur very infrequently thanks to the production methods and controls described previously.

Undulation and DTV.

When pads press against the braking surface they may meet "cavities" or "bumps". Passing over the latter they are forced back towards the piston and these alternating movements (right pad, left pad) cause vibration. When this phenomenon arises, possibly a few hundred or thousand kilometres after installation, the vibration starts gradually but then becomes more intense as the distance travelled increases.



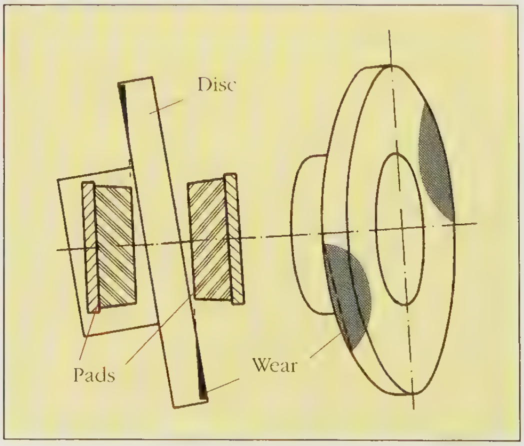
Surface deviation during one rotation

Disc thickness variation during one rotation

In certain cases the pads oscillate and vibrate in the absence of braking action, for instance when travelling on a motorway. They touch against the disc and cause a *facet-type* wear. The end result is almost the same as a production-type DTV. In other cases, a new disc that has a pronounced wobble due to installation will cause a similar type of pad wear and after a few thousand kilometres will present the same symptoms. A disc thickness variation equal to or greater than 35 mm is sufficient to make vibrations felt, even though this will differ from car to car.

If a disc is undersized or badly designed, distortion may occur as a result of a significant temperature increase. When it cools down it does not return to its original shape and the wobble this causes will lead to irregular wear and, after a certain distance, the appearance of cold judder-type vibrations.

Formation of DTV.

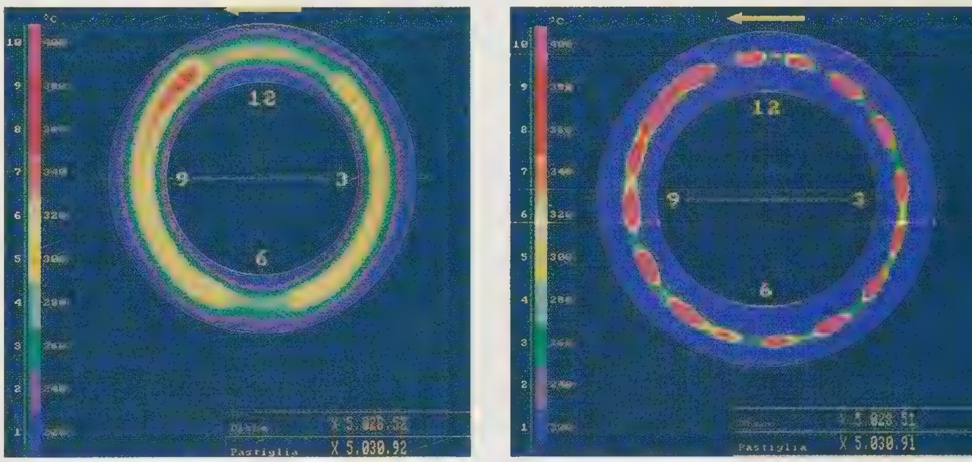


If the vibrations appear after or during exposure to high temperature then the phenomenon is known as **hot judder**. In an at-

tempt to cause such vibration a series of average level deceleration braking actions are performed while speed is increased up to 90% of top speed. For instance this type of test resembles leaving a motorway: speed is high while braking action is average but prolonged since it continues until the vehicle comes to a halt. As a consequence the temperature increases considerably. If friction is uniform over the entire disc braking surface, then energy is evenly distributed and nothing critical happens. If friction is more accentuated in one or more points then the energy exchanged at those points will be greater at the outset and there will be a rapid, localised temperature increase. Vibrations appear simultaneously at the hot points, which are normally distributed in a uniform manner over the disc, and these, on cooling, create more or less visible dark patches, or *blue points*. This transformation mechanism, the cause of which can be attributed to pad material (rapid friction coefficient variation, encrustation, etc.) is extremely detrimental and the disc is damaged beyond repair. 2.3.3.2

"Cold" disc with dark patches.

In fact the blue points are a localised conversion of cast iron into cementite - an extremely hard substance. This transformation takes place at very high temperature and is non-reversible: as the blue points will be less subject to wear than the rest of the surface, the phenomenon will spread with each braking action of the type described. Transformation of the cast iron affects it to such a depth that a reworking of the surface would not resolve the problem. During development of pads for a new vehicle the possibility that a certain composition may cause hot judder is sufficient reason to discard it. As a result, pads homologated by the original equipment manufacturer do not have this defect. It should be noted however that use of discs worn down below their minimum thickness can be the cause of this type of deterioration since the temperatures reached tend to be much higher.



Vibrations occur simultaneously with the formation of hot points that, on cooling, create dark patches.

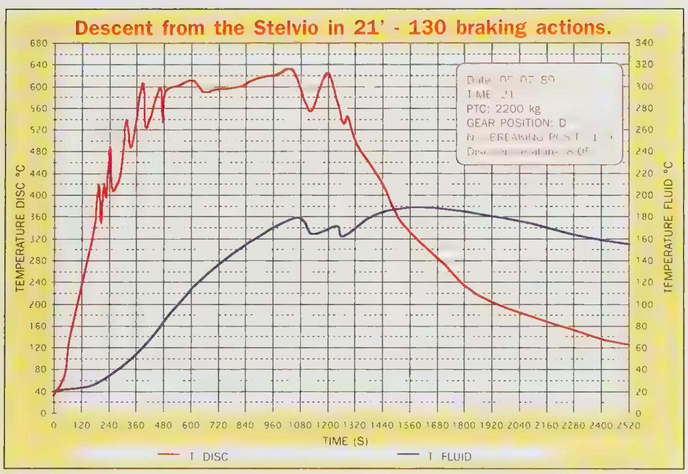
The "**snatching vibration**" phenomenon is the onset of noises that are sometimes accompanied by vibrations. This is due to a variation in the braking torque, the cause of which can be attributed to instability of the pad material's friction coefficient. Incorrect running-in may at the same time be both the cause and the consequence of this. This problem appears in cases of heavy, though not sharp, braking - once again, when the temperature is very high.

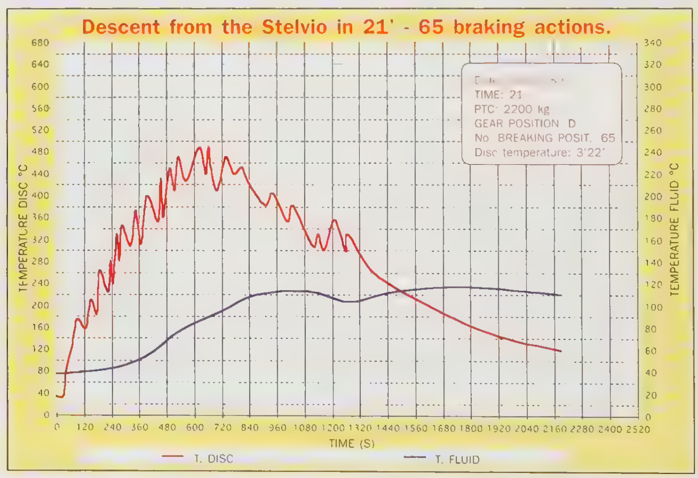
2.3.3.3

2.3.3.3 TESTS UNDER EXTREME CONDITIONS

Alpine tests are a special kind of road test. While perhaps they do not provide the same quantity of scientific results as laboratory tests, manufacturers use them because, on the one hand, they enable safety checks to be made and, on the other, they allow comparisons of technical levels to be made since they have been performed for decades. The Alps provide a number of suitable routes: the Stelvio in Italy, the Gross Glockner in Austria and the Ventoux in France. All of these roads lead down from a pass and generally comprise downhill sections with a pronounced, uninterrupted slope (about 10%) for at least ten kilometres and have no flat or uphill stretches. There are two types of tests: those conducted at average speed that envisage a long series of braking actions so that the temperature increases in an exaggerated manner, and fast descent tests. On the Stelvio, for example, three speeds of descent are used from the pass down

Temperature curves recorded during a descent from the Stelvio.





to Gomagoi: 23, 21 and 19 minutes. After testing, a detailed analysis of brake components, particularly the disc, is performed.

Map of the Stelvio test route.

It is also interesting to compare two 21-minute descents, each performed using a different driving style. The first descent involves braking a high number of times (130) which means that the brakes are activated for a total of fully 8 minutes and 5 seconds. This style

2.3.4

also means resorting to bursts of rapid acceleration to make up lost time. The other descent involves braking only 65 times, equal, that is, to 3 minutes and 22 seconds. In the latter case the temperature of the brakes, but also of the brake fluid, increases much less. The first type of descent is dangerous because the brake fluid temperature almost reaches the boiling point of a new fluid. We will see later that the boiling point decreases when used fluid contains a little water, a factor that increases the risk of malfunction during braking.

These tests under extreme conditions sometimes reflect the driving style of certain users; they can cause irreversible deterioration of the disc and pads as will be seen later in Chapter 3.

The comparative test on the Stelvio descent provides a concrete indication of the type of braking to adopt in order to keep the system in good shape. It is advisable to avoid long, low pressure braking action (when approaching a motorway toll-station, for example), as this increases the temperature of the discs and pads. Whenever possible (depending on road conditions, traffic, load and passengers) try to brake for as brief a period as possible.

The road down from the Stelvio pass.

2.3.4 NOISE ANALYSIS, LOCALISATION AND ELIMINATION

The notion of comfort plays a fundamental role in the choice of a car, especially in the case of top of the range models. It is therefore essential to eliminate all repetitive and fastidious noises and vibrations. Engines today run more silently and are better soundproofed, as is the exhaust system, than they once were. In effect components no longer start to vibrate heavily when resonance is produced at high revs. This is why braking noises - should these occur - are not at all well tolerated. While in the majority of cases braking noises are by no means a sign of reduced safety they do force users to visit their garage urgently in the search for a remedy. Noise can be said to be an almost natural consequence of friction. If you hit something with a hammer there is noise because whatever you hit vibrates. During braking a number of micro-impacts occur between the pads and disc that may cause them to vibrate. If the system becomes unstable at frequency •, the braking system produces a whistle at the instability frequency •. Another possible comparison is with an old-style gramophone: the brake disc is the record, the pad is the needle whereas the caliper and bodywork act as the horn.

Brake designers have to ensure that there are no noises, but the problem they face is extremely complex. In fact, as we will see, the question of noise involves many aspects since the causes, if not highly numerous, are still many. The disc is the transmission agent although the origin is always friction. As no miraculous cure exists for this problem, technicians have developed a number of analysis techniques to identify the origin of noises and also various solutions that can be adapted to each case as it arises.

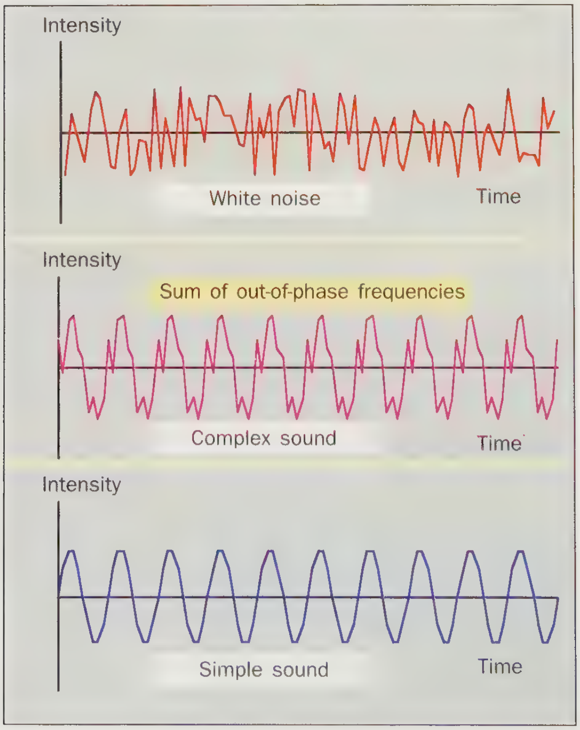
2.3.4.1 NOISES

Noise is an **acoustic emission** that is normally perceived as something unpleasant whereas music and speech - although they are also acoustic emissions - are almost always pleasing sounds to the human ear. There are two reasons for this: the first is subjective while the second is of a more scientific nature.

The first reason regards the level of acoustic emission. In fact, even if a piece of music is considered sublime, if it is played at a level near to the pain threshold it is considered as a noise because listening to it is unpleasant. The second and real reason derives from the fact that a noise is the superimposing of non-harmonic sound frequencies and comprises much discontinuity and phase changes.

Simple sound, complex sound, noise and white noise.

Sound is a sinusoidal oscillation of air pressure. This oscillation is created by the vibration of a solid and is perceived by man through to the structure of his inner ear. In the case of an elementary sound, there is one single vibration **frequency**. A complex sound is due to the superimposing of vibrations having different frequencies. When the frequencies are multiples of the lowest frequency they are said to be **harmonic**, an instance of this being the sound made by a musical instrument. The difference in terms of distribution based on intensity for the harmonics produced by two instruments is the main reason why a distinction is made between the note *C* on a piano and that on a violin. Without going into the rules of harmony in detail, it is sufficient to say that if one were to press two adjacent keys on a piano simultaneously then it would start to bring home the concept of noise. Taking the extreme case, there is what is known as **white noise** that comprises all of the frequencies that can be included in a



merely random sequence of intensities. This means that the intensity at any given moment is by no means the consequence of the intensities produced an instant before. Braking noises are not white noise as has been shown by spectrum analysis. 2.3.4.1

The **intensity** of a noise should be measured as a pressure variation. However such a unit would not be easy to use as the human ear does not perceive sound as being proportional to pressure but to the logarithm of the pressure. This is why sound intensity is measured in **decibels**. This logarithmic scale requires a starting point which has been established as the smallest variation in pressure that the ear is able to perceive, namely, 20 micro-Pascal. On the other hand it is a well-known fact that the threshold of perception depends heavily on the frequency of the sound. An adult with good hearing can only hear sounds well between 15 and 20,000 Hertz.

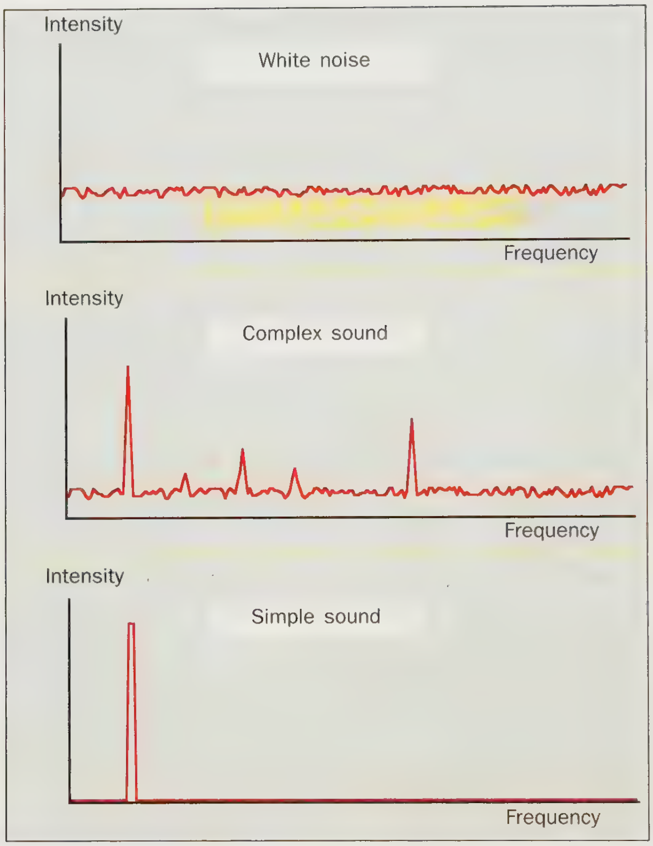
Recording the intensity of a noise or a complex sound as a function of time gives a completely disorganised view. In order to represent this result in a clear manner it is represented on the basis of a frequency curve as opposed to a time curve. In fact it can be demonstrated that any acoustic signal is the superimposing of different frequencies and intensities of elementary sounds. When the noise persists, the intensities remain constant; when the noise decreases the intensities diminish, each according to the law underlying the cause of its emission. Even an impact - namely, an emission of noise for a very brief period - can be broken down into a series of frequencies distributed in a regular manner. Equipment used to perform this type of analysis employ a mathematical function known by the name FOURIER transform or, more often, by the acronym FFT (Fast Fourier Transform). Besides intensities and frequencies, a further important data item is the difference in **phase** between two vibrations. One of the difficulties encountered when analysing complex noises like those in braking is the discontinuity of the emission and the frequent phase change. In fact performing a valid analysis of a noise requires the recording of it for a time corresponding to numerous periods of the sound with the lowest frequency. This period may last just a few seconds during which the highest frequency sounds

$$\textit{Intensity in decibels} = 20 \cdot \log\left(\frac{\textit{Pressure intensity}}{\textit{Audibility threshold intensity}}\right)$$

Intensity in micro-Pascal	Intensity in decibels	Type of noise
20	0	audibility threshold
100	14	quiet forest
2 000	40	library
20 000	60	animated discussion
63 000	70	noise of a car
630 000	90	noise of braking
6 300 00	110	the Rolling Stones
35 500 000	125	jet plane taking off
200 000 000	140	pain threshold

2.3.4.2

Frequency breakdown for a complex sound and a noise.



may change phase many times. Recourse therefore has to be made to more complex methods.

2.3.4.2 BRAKING NOISES

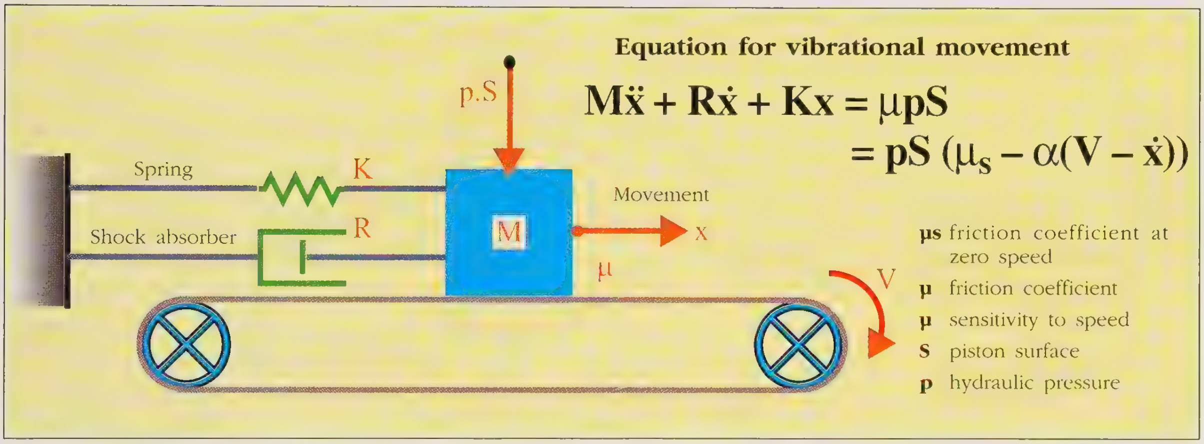
Three factors must exist in order for there to be a noise: an **excitation**, a **resonator** and an environment for its **propagation**. Of course we should not forget that there must be someone there to hear it and that the frequencies perceived fall within this person's hearing range. Example: a bell is excited by the impact of the clapper. A bell is a resonator with its own frequencies, its own note, and the air is the medium through which its acoustic wave propagates. The same happens with a brake: excitation is given by the friction material rubbing against the disc. Energy transfer from the disc to the interface and the pad appears to happen in a continuous manner although in reality it is a succession of more or less rough impacts. The resonator is almost always the disc although it can be the pad, the caliper or a combination of these various components. In the section on modal analysis we will see that any object subjected to an impact, even a slight one, vibrates for a certain length of time.

The vibration **modalities** of a component are not left to chance but are closely linked to the geometry of the item concerned and the physical properties of the material from which it is made (for example, density or elasticity modulus). Following excitation, vibrations dampen and finally disappear. While normally metals - particularly ferrous metals - are not good dampers, grey cast iron does have a damping effect, although both friction materials and tyres are much better dampers.

Noises in brakes are rarely produced by the vibration of a single element since all components come into contact during braking, a fact that makes analysis and

2.3.4.2

identification of the causes much more complex. Numerous researchers have attempted to describe and classify models to represent the various types of noise generation in brakes. Among such studies, that conducted by A.M. LANG, N. MILLNER and M.R. NORTH should be mentioned. The various models proposed give a good explanation of the different origins of braking noises although these will not be examined in detail here. We will only refer to and describe them briefly here, while readers are invited to consult publications listed in the bibliography for more in-depth information.
To explain low frequency noises, namely those less than 200 Hz, the best known model is referred to as "non linear **stick-slip** vibration". This simplified model



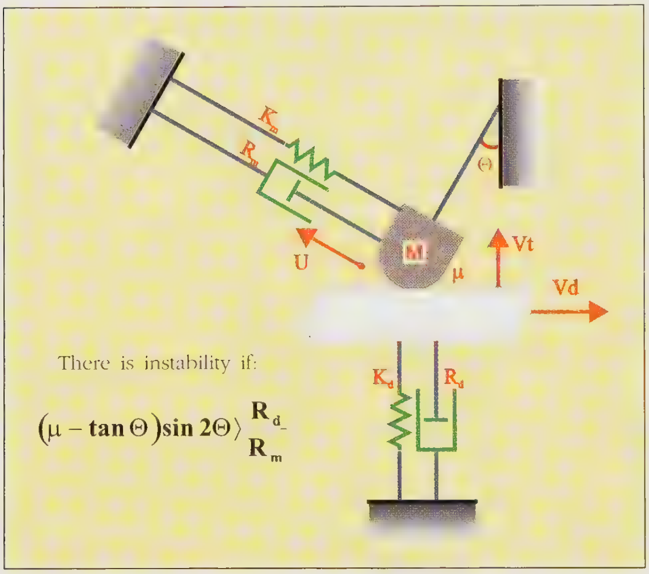
shows a fragment of pad material rubbing against the disc (here shown as a surface in motion) and connected to the caliper by means of a viscous-elastic system, that is, comprising a spring and a shock-absorber. This model assumes that the friction coefficient is unstable and varies in a linear manner with the rotational speed of the disc relative to the pad. The equation shows that damped vibrations will be generated, regarding which sensitivity to the speed of the friction material is a significant factor.

Instability of friction coefficient.

Complicating the model, in particular by bearing in mind the possibility of caliper vibration relative to the axle, the authors have highlighted the possibility of vibration emissions in the 200 to 400 Hz range. These noises are sometimes referred to as "Hum" or "Moan". In such cases the manner in which the caliper is attached is the important factor.
Higher frequency noises, in the 500-13.000 Hz range, are often referred to as **squeal**. The model shows, in principle, how a disc can vibrate of its own accord and that the vibration frequencies noted are the same as those found in the noise produced.
The term **squeak** is used to describe the mechanism generating even higher frequencies, from 2 to 5 kHz. This mechanism brings both the disc and pad joint-

2.3.4.3

ly into play. When the disc vibrates and distorts to form four or five lobes, the width of each lobe measures approximately the same as the length of the pad. As a consequence, the latter is pushed away alternately from right to left (from top to bottom in the illustration): this is the excitation movement. The pad also has its own mode and therefore starts to vibrate. As it is in an unstable equilibrium on its own supports relative to the caliper, the latter vibrates too. Given that the size is less than that of the disc, the frequencies will be higher.



"Cantilever" model.

Other noises, for example that referred to as "metal brush", are the result of a superimposing of a number of squeak-type vibrations, first damped and then again excited. Such noises, that bring into play the components' own modes, have frequencies that are not dependent on the disc's speed of rotation.

Lastly it should be noted that from both the theoretical and practical standpoint, an increase in friction coefficient tends to increase the probability that noises will appear.

2.3.4.3 METHODS FOR ANALYSING BRAKING NOISES AND THEIR CAUSES

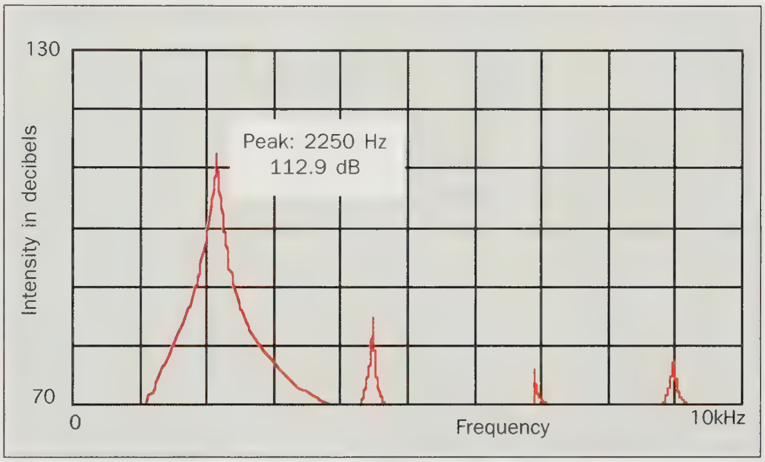
The first method of analysis naturally consists of measuring the noise intensity with the aid of a **phonometer**. This method requires generating the noise and placing a microphone at a clearly established point, usually outside of the vehicle. The recording will enable more detailed analysis to be carried out. In essence the different frequencies and their intensities are separated out by means of **spectrum analysis** using what is today quite commonly used equipment and that includes a computer which can process the signal's FFT. Such equipment is portable and can be installed on board the vehicle.

The frequencies detected by the spectrum will provide initial indications towards finding a solution. This type of analysis can also be performed in the laboratory, for instance using a **dynamometer**. However it usually requires a more complex brake assembly compared to that used for friction measurements. In fact the brake environment must be reproduced and this, for example, implies fitting a wheel to the disc or even installing the complete suspension. This method pro-

2.3.4.3

vides almost identical results to those achieved on a car and is particularly productive because tests can be automated and therefore a greater number of situations can be analysed.

As we have mentioned, when an object is subjected to impact, however slight, it begins to vibrate and may emit a noise. These vibrations are by no means random and in particular do not depend on the excitation except in terms of their intensity. Let us take the case of a disc. The first type of distortion is the conical shape that develops in the carrier, first in one direction and then in another. The second type is similar to the first, except that the two opposed parts of the carrier move in the opposite direction. The following types are more complex and involve the formation of an even number of lobes as if the disc has been subjected to radial undulation. These different folds vibrate alternately. Certain of them move in the same direction and are simultaneous: they are in phase. Others vibrate in a counter-phase manner. The points located on a radius that vibrate with a higher intensity are called "loops" whereas those with zero movement are called "nodes". As far as a disc is concerned, their positions are determined by the point at which the initial impact occurred, since this is a loop. Each single frequency has its own mode. For example, as the vibration modes all take place simultaneously although with different intensities when excited by an impact, the sound emitted will be the superimposing of all of the **discrete frequencies**.



Braking noise spectrum.

If the disc is no longer excited by an impact but by a vibrator, it can be noted that the disc only vibrates at frequency excitation values corresponding to one of its own frequencies. In this case it is said that resonance exists. It is possible to measure such frequencies and distortions by repeatedly striking the disc at the same point with a hammer and by positioning the accelerometers at various points over the disc. The hammer is fitted with an electronic device that provides the start signal for measurement.

Modal analysis is very useful as it illustrates how a disc distorts and what effect either geometrical or weight modifications might produce. In recent years other investigation techniques have been developed relative to braking noises and their generation. Using **laser holography** it is possible to make an object's state of distortion visible at a given moment. Little testing time is required since this corresponds to the time needed to take a photograph, that is more or less

2.3.4.3

Modal analysis.

one thousandth of a second. This complex method is particularly interesting in cases where the noises emitted are very unstable as a result of vibrations that are themselves discontinuous. The principle is based on making interference fringes appear on the surface of the vibrating object, not due to height differences but to temporal positioning differences of each point of the object examined. A high-power laser beam is used to produce a hologram, namely a three-dimensional photograph, that is processed to trace the level curves corresponding to the fringes. This is an extremely complex procedure and can only be carried out in a specialised optical laboratory.

Analysis of a disc using laser fluxometry.

The coherence of laser light is also used in **laser fluximetry**. In this case measurement takes only a few seconds and it is much easier to perform. The principle is based on the well-known DOPPLER effect according to which, for example, if one were to stand near to a railway track and listen to the whistle of a train in motion, the frequency, even though originally fixed, changes continually from the standpoint of the observer. The same can be said of light. When a laser beam is directed at an object and reflected, the frequency of the reflected light is different from the original frequency. The difference is proportional to the speed of movement of the object in question. Surface exploration of the object under examination using a laser beam and permanently measuring the variation of the wavelength of the reflected light makes it possible to map the speed of movement of the various points on the object. This method is much easier to perform than the one mentioned previously although it can only be applied if the vibration remains stable for at least the entire duration of one exploration. This becomes a limitation in the case of very complex noises.

2.3.4.4 SOLUTIONS FOR ELIMINATING NOISES

2.3.4.4

The aim of all of the analysis techniques we have mentioned is to highlight the cause of noise generation. In fact it is very easy and effective to search for corrective measures once the cause of the problem is known. The first method, although not always easy to apply, consists of modifying aspects of **geometry** to alter the frequencies in question, so avoiding resonance instability. Machining, feedheads and springs can sometimes resolve the problem without resorting to a complete redesign of the braking system. The second category of modifications concerns the **friction material**. This solution often has to be adopted for braking systems that have remained unchanged for long periods, but it is not always the best. The technician formulating the pad material will attempt to modify certain characteristics such as stability as a function of speed, the change of aggressiveness due to use at high temperature or will alter certain of the material's physical properties, like density, dynamic elasticity or vibration damping power. It has to be admitted that in many cases this leads to an overall decrease in friction level. Another method is to interrupt the possible transmission of vibrations between brake components and also to its support attachment. Attempts can involve either making contacts more rigid or, alternatively, damping them.

In the spirit of this approach friction material producers supply pads with a damping layer attached to the back. This is the so-called **anti-noise** layer or *shim*. In the simplest cases it consists of a backing produced from a type of rubber-based paint, but it can also be achieved by bonding on a sheet of complex lamellar material. Certain suppliers prefer more complicated solutions such as alternating two or three thin metal plates and sheets of rubber, plus a film of bonder. The desired effect may simply be to dampen the transmission of vibrations between the piston and the pads or also to modify the rigidity of the support in the case of a squeak-type noise.

Pad and shim.

Progress made in the automotive field during the latter part of the 20th century has been considerable but would require too much space here to describe fully. It is however useful to underline that the broad issues addressed have been an increase in safety, weight reduction, lowering of fuel consumption, improvements in comfort and a considerable increase in reliability. This latter point has led to two advantages: a longer interval between scheduled service interventions (on average, every 15,000 km) and a reduction in the number of components requiring substitution during the vehicle's useful life.
In spite of this progress, certain parts need to be periodically checked and replaced in order to maintain a high level of safety and reliability for the system as a whole. Almost all the parts that require replacing are subject to wear in the tribological sense of the term. In fact, the purpose of each such part involves a rubbing action against another one, as in the case of windscreen wipers, belts, discs and pads. This, of course, without overlooking items that need to be replaced more often, namely, oil and filters. In fact oil - apart from its role as lubricant, coolant and corrosion protection agent - also gathers waste material lost as a result of wear by parts that move or rub against one another.
The braking system must be checked at every scheduled service and components that have either exceeded recommended wear levels or present signs of deterioration must be replaced. It is essential that such maintenance be carried out by **specialised mechanics** who possess complete **documentation** and have periodically undergone **training** on the new products for which they are required to provide assistance.

3.1 ANALYSIS AND DIAGNOSIS

Braking system maintenance can occur in one of two circumstances: during a general check-up or when the user has a problem. In the latter case, braking system producers provide flowcharts to help identify the cause, however, such flowcharts are very exhaustive and therefore too voluminous to present here. On the other hand, as can be imagined they cover aspects concerning the braking circuit, pads and discs. The ABS is also covered although an attempt to discuss it here would sidetrack us from the main issues involved.

3.1.1 THE CALIPER AND CIRCUIT

This check is normally carried out when the pads are changed. In fact the pistons progressively protrude more from the caliper as the friction material wears down and need to be pressed back before new pads are installed. Before doing this it is advisable to check the level of the brake fluid in the tank. If the latter were already full then pressing back the pistons would cause an overflow of brake fluid. Under no circumstances **must the brake pedal be pressed** while performing this operation. It is normal for the fluid level in the tank to gradually reduce as the pads and disc wear down, however, it must never be allowed to fall below the minimum level. Similarly, if after replacing the pads, the level still remains low then this is an indication of a leak in the circuit. When pressing back the pistons a check should be made that they move freely within their cylinders. Were this not the case, then they must at least be "greased". Care however, must be taken that the pad and disc surfaces are not contaminated with grease. If greasing is not sufficient then the caliper and pistons should be dismantled, after first bleeding the fluid from the circuit. The manufacturer's technical manual should be consulted before attempting this operation, particularly since the gaskets will have to be replaced, which is a very delicate operation. First of all clean the parts and examine the caliper carefully, and then - in the case of floating calipers - check that the guides run properly.

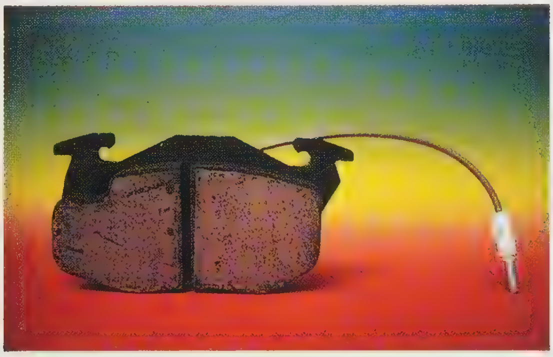
Pistons and gaskets.

The initial check to perform on the braking circuit is to establish if there is any loss of brake fluid. This operation first requires that the circuit be cleaned externally. The brake must then be activated at a high pressure if there is a brake servo, as is often the case today. In order for the servo circuit to function, this operation must be performed with the engine running.
Poor braking may occur if surface dirt has not been removed from the hub before refitting the disc or if there is play in the bearing. In the latter case, the effect will be the same as that of a disc run out error and it will therefore be necessary to replace the bearing. Defects that may arise due to malfunctioning of the brake servo, master cylinder or ABS will not be described here in detail even though it is recognised that these can cause poor braking performance.

3.1.2

3.1.2 THE PADS

The main cause of pad replacement is normal wear of the friction material. This requirement is provided for and expected since the majority of pads are fitted with a wear indicator. This device sends an electrical signal to the instrument panel when the layer of material covering the metal support pad is less than approximately 3 mm. The most simple type of wear indicator comprises an electric wire located in a hole within the friction material. A current runs through this wire which, when exposed by wear, forms a contact with the disc, completing a circuit through which current passes, so causing the on-board indicator to light up.



Pad with wear indicator.

In reality systems employed today are a little more sophisticated. In fact they maintain information right from the first contact which means an increase in safety but also prevents the indicator lighting up in an untimely or accidental manner. The material still remaining is normally just the substrate, namely a less abrasive material.

Other situations can occur that almost always necessitate pad replacement. The cause of these anomalies requires more detailed analysis. Although such situations are rare, they do in fact arise: this is why pads must periodically be checked - at least every 10,000 km.

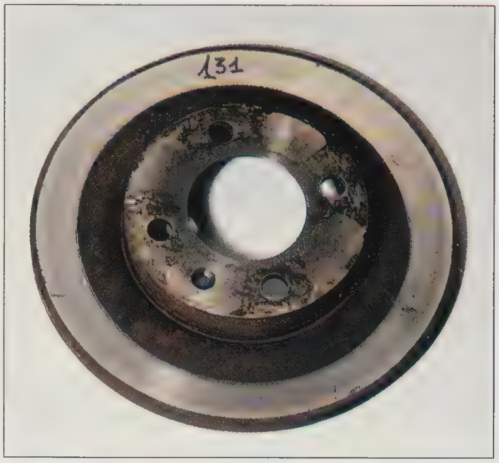
Check on state of components	Actions to be taken
Wear indicator is in contact with the disc.	The pads need to be replaced.
Wear indicator circuit is interrupted or missing.	Requires repair or replacement.
Pad cracked or flawed.	Requires replacement. Analyse the question more closely.
The pad has detached from its metal support.	Requires replacement.
Trace of brake fluid or grease on friction material.	Requires replacement. Check the loss of fluid.
Grooves or scores (pad and disc). Tolerance for the disc is 0.3 mm.	No action required if pads and disc are within the tolerance.
Wear of one pad is greater than that of the other pad on the same caliper.	Check the calipers and, in particular, movement of the pistons.
Uneven or oblique wear of one or more pads.	Check positioning of the accessories, the correct movement of the pads in their seat and functioning of the caliper.
The assembly accessories or the anti-noise are loose, missing or damaged.	Requires replacement.

3.1.3 THE DISC

This section deals entirely with a more in-depth analysis of the technical reasons underlying a change in disc performance and, as a consequence, the need for its replacement.

We will also summarise the various visual checks and analyses that need to be carried out in order to ensure disc integrity.

The pad only presses against the outer half of the braking surface.



First and foremost it should be stressed that a mechanic is the most qualified person to check the state of wear of a disc. Such wear occurs with normal use and must be checked periodically.

Normal disc wear creates a ridge that runs around the external perimeter and corresponds to an unworn part. This ridge is one of the "wear indicators": when it is clearly visible the residual thickness of the disc between the two braking surfaces should be checked and compared with the minimum thickness etched on the outer rim of the disc.

This measurement alone is not enough inasmuch as a check must also be made to ensure that wear is not **uneven**, namely, that one surface is not worn to a greater degree than the other. The maximum variation, not to be exceeded, is indicated by the manufacturer, although in any event it should not be greater than a few tenths of a millimetre, above all when the disc is quite worn. The caliper must also be checked since wear may be due to defective *roll-back*.

The change in the disc needs to be closely analysed.

The disc may have lost other size characteristics when compared to its new state: **run out**, **planarity**, **DTV**. A closer analysis of these changes - causes of vibration - provides a better understanding of the state of the braking system.

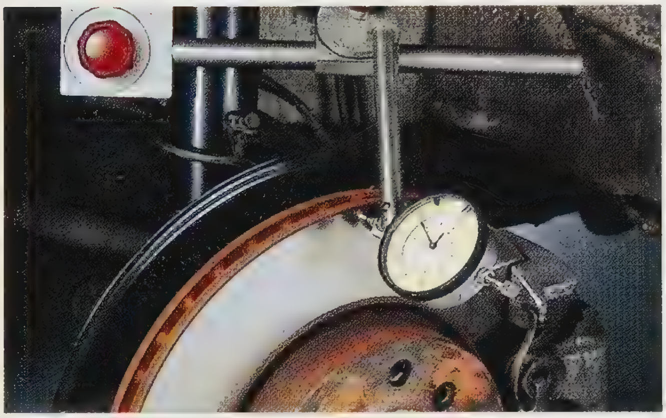
- **Increase in run out**: after fitting and using a new disc, run out can be determined by taking a measurement on the unworn external edge (ridge). Run out can also be measured on the braking surfaces. These measurements are taken with the aid of a DTI Gauge fixed to the suspension by means of a magnetic foot. The onset of run out, not present at the time of installation, may indicate that there is a problem with other components in the braking system. If run out was excessive at the time of installation then the hub and bearings should be checked, because they were probably not checked previously.

- **Change in planarity**: exposure to high temperature may compromise the disc's planarity. As the carrier remains cooler than the braking surfaces, dilation of the

3.1.3

metal and radial stresses leads to distortion of the disc with the appearance of lobes. Part of the distortion occurs at the moment of cooling. The DTI Gauge indicates a series of high and low points (three or more). An incorrect tightening torque of the bolts securing the disc to the hub causes loss of planarity.

- **DTV behaviour**: different thickness of the braking surfaces, a consequence of uneven wear due to the two problems described previously, causes the onset of vibrations that become considerable when the value of the disc braking surface thickness (DTV) exceeds 35 μm.



These measurements are taken with the aid of a DTI Gauge fixed to the suspension.

The disc should be inspected carefully after, or at the same time as, measurements are taken.

In certain cases **superficial corrosion** - namely, rust - can be observed, due to prolonged presence in a damp environment. If the disc is not worn, then such rusting is no cause for replacing the disc. However, a certain number of braking actions should be performed - similar to the running-in procedure - in order to eliminate the corroded layer. If the corrosion remains on only part of the braking surface after normal use this is due to poor caliper functioning: the caliper should therefore be checked and either repaired or replaced.

A presence of deep **circular grooves** or numerous **radial cracks** extending for more than a few millimetres are unquestionably indications that the discs must be replaced. Lastly, the presence of **dark patches** or **blue spots** is a cause of vibrations. If this phenomenon is rather pronounced and, above all, if the driver is disturbed by them, then the disc must be replaced.

The previously mentioned factors indicate that the disc has lost its original mechanical and chemical properties and has become the source of vibrations (hot judder). For simplification purposes, we have often referred to the need to replace "the disc". In effect both discs on the same axle must be replaced.

Furthermore, apart from instances of normal wear and corrosion, cases of abnormal wear do not only involve replacing discs. Such cases in fact point to faulty behaviour by other components within the braking system and this needs to be carefully investigated by a specialist. The latter should moreover give this information to the driver and communicate it to the supplier companies concerned. Clearly this comment does not just apply to brake discs.

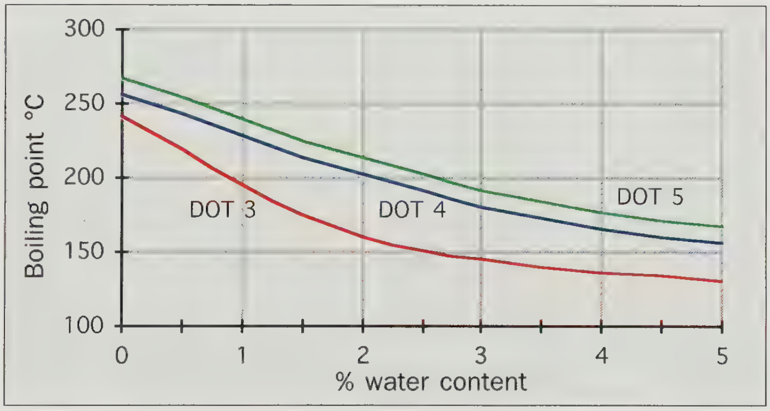
Even if only one disc needs replacing it is absolutely necessary to replace both discs and pads.

3.1.4 BRAKE FLUID

3.1.4

Transmission of force from the pedal to the pad has changed greatly from the times of early cars. Initially it was an entirely mechanical process. It then became pneumatic, and finally hydraulic. Air transmission is still widely used on heavy trucks as it is both efficient and convenient - among other factors, it facilitates the connection and disconnection of trailers. On the contrary, compressed air systems occupy a lot of space and are therefore not suitable for use on cars. As a result, the transmission system invented by Malcolm Loughead has become standard. Just as one refers to a "Hoover" to indicate a certain home appliance, the term Lockheed is often used in the brake field to indicate the fluid - Lockheed was the name of the company that Loughead formed. Brake fluid must meet a certain number of requirements:

- it must be a **non-compressible fluid** under normal use conditions;
- it must have a **high boiling point** in order to remain in a liquid state even in extremely severe braking conditions;
- it must have a **low viscosity** even at temperatures near to its freezing point, which must not be higher than -40°C;
- it must be a **lubricant** so as not to cause seizure of moving parts (master cylinder and pistons);
- it must be **chemically stable** and not have an aggressive action on braking system components in order to avoid corrosion;
- it must be an **inert** fluid as far as rubber parts - the **gaskets** - are concerned and furthermore must not act as a solvent.



Brake fluid boiling point curves.

As modern fluids possess all of these properties it could be thought that they do not need to be checked or maintained. Nothing is further from the truth! All liquids that meet these requirements are essentially of organic origin and their molecules have polar properties as, for instance, in the case of glycol or its esters. These properties render such liquids **hydrophilic** or **hygroscopic**. This means that in the presence of water vapour the fluid fixes water molecules by means of weak bonds, a fact that affects the boiling point enormously. In fact the system is not airtight and so damp air can enter the tank as the fluid level drops. Humidity is progressively absorbed by the fluid up to a certain limited percentage which is, however, enough to lower the limit at which the first gas bubbles - essentially, water vapour - appear. Unlike liquids, one of the properties of gases is that they can be compressed. When bubbles are present within a circuit, pressing the

brake pedal causes them to compress, slack increases enormously and pressure in the system does not reach the required values; braking action is thus completely inefficient. This phenomenon is known as **Vapour-Lock**.

The only way to avoid this very serious problem is to check and replace the fluid periodically. Manufacturers' maintenance manuals recommend that this be done annually. All mechanics should have **boiling point measurement** equipment to check the state of fluids. The rate at which a fluid absorbs water is to a large degree determined by the climate. A value of 3% can be reached in one or two years, corresponding to a decrease of about 80°C in the fluid's boiling point. Furthermore the presence of water increases the risk of corrosion within the circuit. After changing brake fluids it is absolutely essential to **bleed** the circuit since, in this instance, there could be air bubbles that may impede reaching high pressures. There are a number of types of fluid that have been homologated by the US Department of Transport, referred to as DOT3, DOT4 and DOT5 based on their performance.

Brake fluid test equipment.

3.2 REASONS FOR REPLACING DISCS

Experience indicates that drivers believe discs are hardly ever replaced. As a result, when a mechanic says that he has done so, customers suspect that either the braking system is defective or that he is being cheated. Usually this is not the case since wear is a normal occurrence. There should be no hesitation in replacing discs once they have worn down to minimum thickness. As we will show, safety is not compromised immediately when a disc is too worn, however, it can be in a very short time.

3.2.1 WEAR AND CRACKING

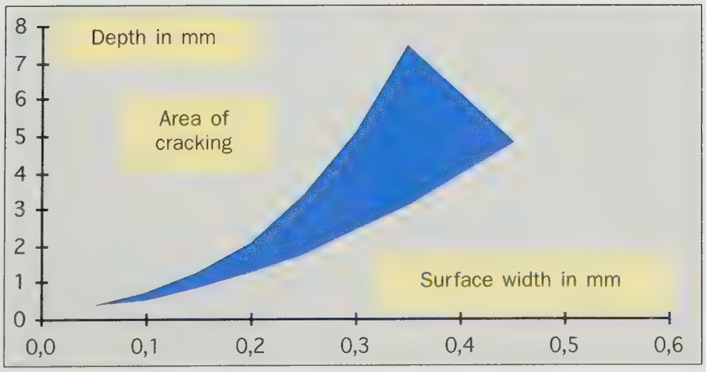
While a disc's braking surfaces wear down systematically, even though the speed at which this occurs varies, cracking, on the contrary, does not always appear. It is by no means unusual however to find this type of deterioration. This "ageing", that represents a transformation of the cast iron, normally occurs when the disc is well worn. This is why it is discovered when discs are replaced. Very complex

3.2.1

and in-depth studies have been conducted on this phenomenon that can become very serious. Firstly, it can be ascertained that cracking occurs when the disc's surface is subjected to very high forces and energy transformations as a result of braking action. Therefore, as this is essentially a problem of dimensions, such deterioration is found more rarely on cars when the braking system has been correctly dimensioned and includes an ample margin. Even so technicians still manage to devise very tough tests that cause cracks to appear in new discs. Cracking as such is not detrimental to safety, but it can be an early sign of a breakage to come and this is a much more dangerous matter.

Cracking in the form of fissures.

The mechanism by which cracks are formed has been studied very carefully. Here, we will merely outline the principles. As we have seen, during braking the disc's surface temperature is much higher than the internal temperature and, as a consequence, surface dilation is much greater. The surface is also subjected to a strong **compression force** exerted by the pads. If this force exceeds the material's limit of elasticity then distortion begins to take place when the disc cools down, and cracking occurs. Clearly this does not occur as a result of the first thermal excursion but after a large number of cycles. This is what is normally referred to as **thermal fatigue**. Examination under the microscope reveals that small cracks very often start at a point where there is a heavy concentration of graphite scales. A very homogeneous cast iron will therefore be less subject to this phenomenon. Cracking takes place gradually. Initially the cracks are very small and what is referred to as *fissuring* can be observed. Instead when cracks are more evident they can be seen to run radially across the disc's surface. This occurs because of a complementary mechanism. In the first chapter we saw that the surface of the disc is subjected to traction forces during braking, perpendicular to the direction of pad movements. This mechanism tends to create cracks: it is known as **mechani-**



Stresses within the cast iron of the disc.

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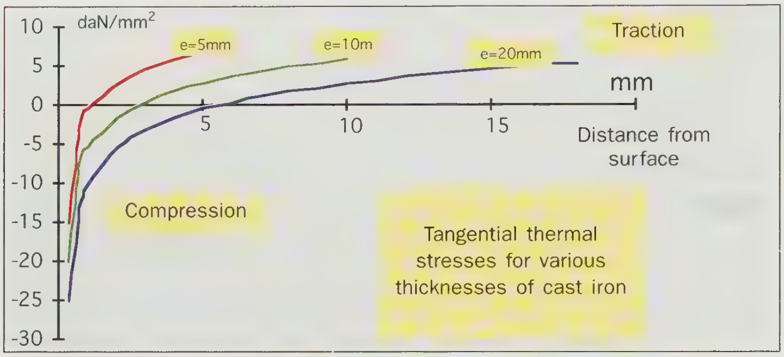
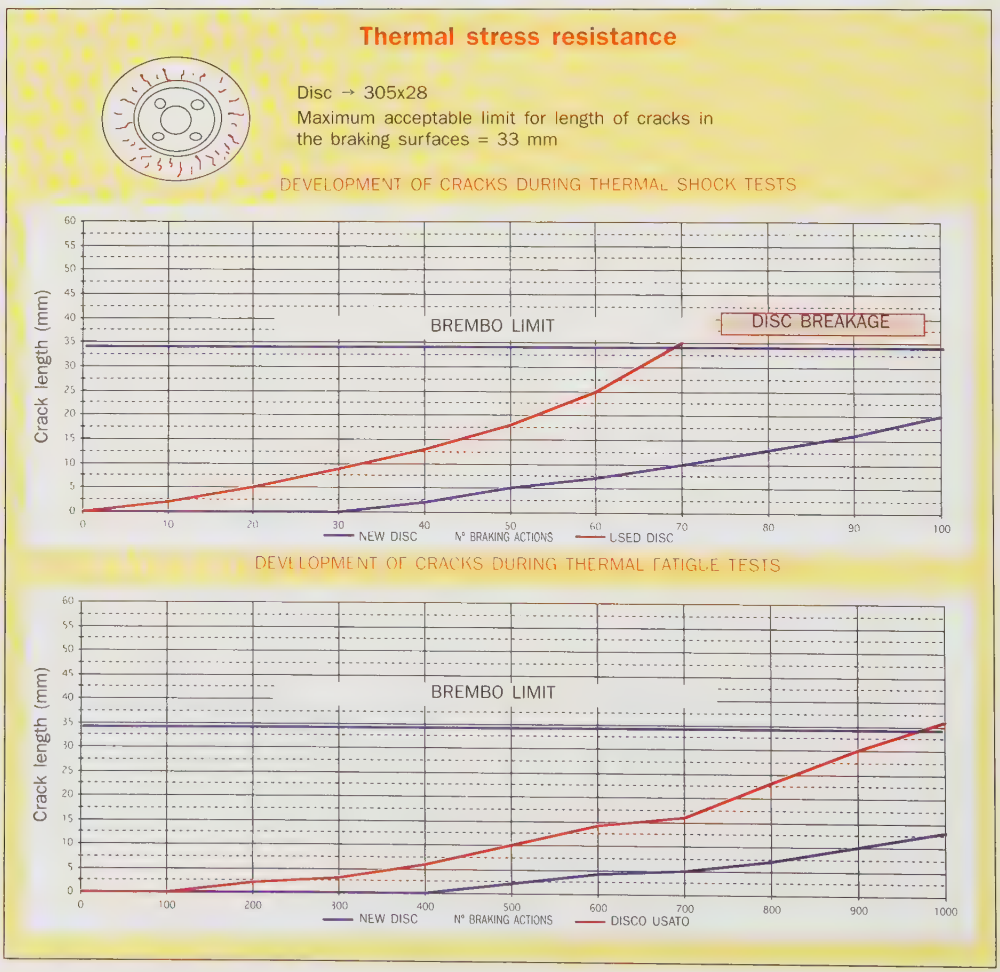


Size of cracks in terms of width and length.

cal fatigue. Studies on a number of sections have shown that the depth of cracks increases more rapidly than their length.

The so-called **"thermal shock"** or **"thermal fatigue"** tests clearly show that cracks proliferate with an increase in braking. Moreover it can be noted that disc thickness has a considerable effect on the cracks' speed of growth. Comparison between a new and a worn disc is sufficient to show this. In order to speed up tests, a new disc is prepared that is already at the minimum thickness level. It is evident that when cracks a few tenths of a millimetre long can be noted on the disc surface, the component must be replaced, since the widen-

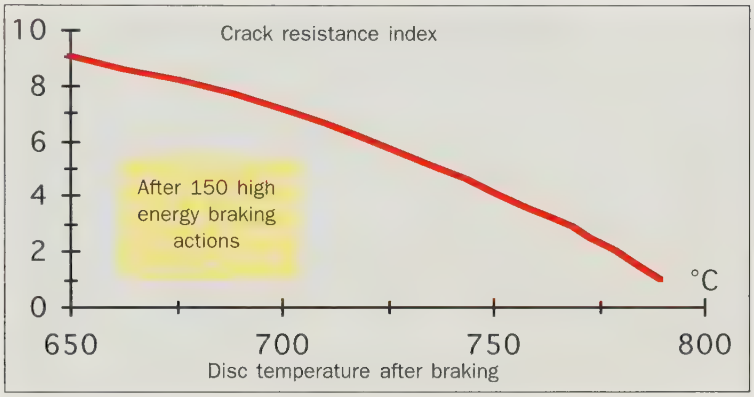


Impact of disc thickness to proliferation of cracks.

3.2.2

ing of such cracks can provoke breakage, often in the space between two blades in the disc's braking surface area. Apart from the fact that braking efficiency may be compromised, this also causes rapid pad deterioration as the disc effectively acts like a rasp. The studies mentioned previously have highlighted the main causes for development and proliferation of cracks. Certain solutions exist to resolve this problem.

- The **thermal conductivity** of the main components in the braking system has to be increased so that lower temperatures are reached; in particular, **pad material conductivity** must be higher, though without creating vapour-lock;



Crack / temperature relationship.

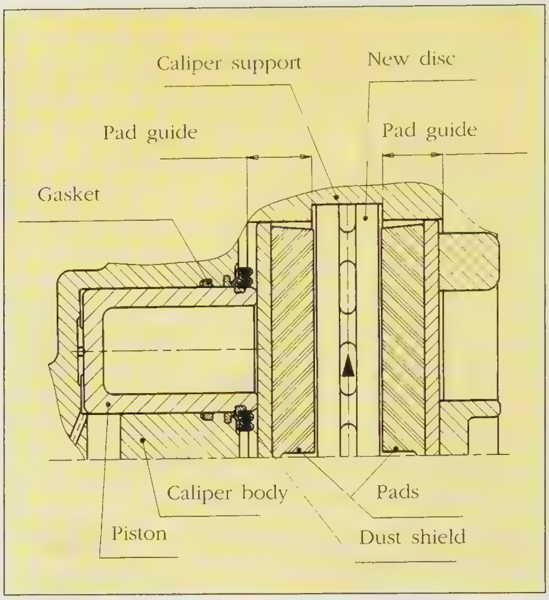
- the pad's **YOUNG modulus** - namely, its elasticity - also has a certain effect in as much as the friction surfaces have to be increased in order to reduce localised mechanical stresses. To achieve this the two surfaces must complement each other, both in terms of the wear effect and as far as distortion is concerned.

In addition to these recommendations, clearly every possible action must be taken to reduce temperature: above all, the cooling of the disc and its dimensions.

3.2.2 WEAR, MINIMUM THICKNESS AND TEMPERATURE

Wear is a normal occurrence although it is not mandatory in order for the brake to function properly. A great deal of progress has already been made in the materials' area and it is quite likely that there will be further progress in the future. In spite of this, however, we have not yet discovered a friction system that has all the characteristics necessary for correct braking but that is not subject to wear. First, a distinction must be made between cast iron wear and friction material wear, above all because too often there is a tendency to attribute both of these types of wear to the pads. This is due to the fact that disc material remains the same (variations in the composition of the various alloys are minimal compared to mixtures used for pads), whereas to achieve certain compromises, pad materials vary much more. As far as wear alone is concerned, materials have been identified that show little wear but that cause a lot of wear in the disc, and vice versa. Faced with such a choice, car manufacturers tend to choose the second option.

3.2.2

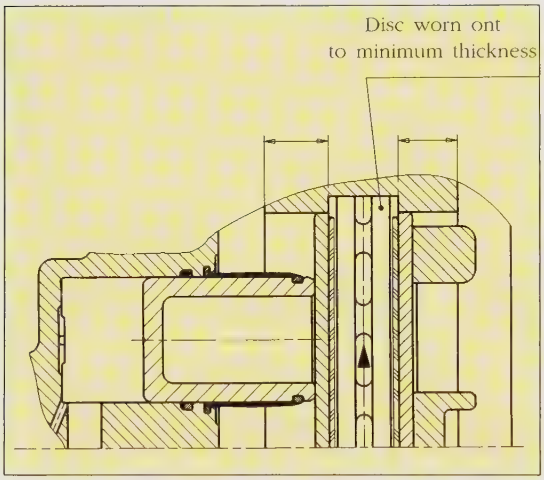


New disc / new pads.

Mechanical consequences of disc and pad wear.

We will also see that there is an interaction between the two types of wear and that replacement of the discs is just as important as similar action with regard to the pads, both in terms of braking safety and comfort levels.

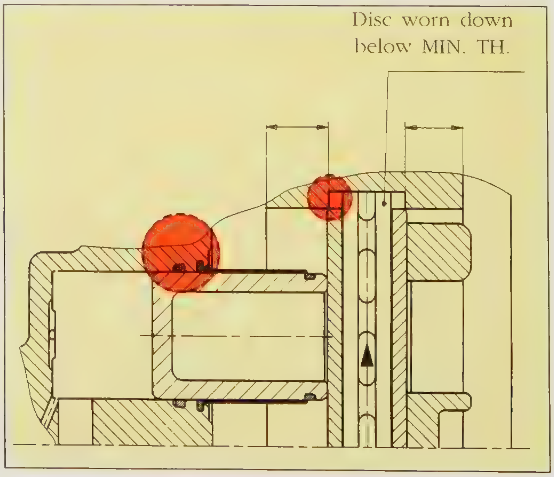
The concept of **minimum thickness** for a disc is so important that the value is etched indelibly on its outer rim. This value is set by the manufacturer for at least three reasons. First and foremost for mechanical reasons: in the case of ventilated discs the cast iron plate must not distort as a result of pressure. Secondly, for reasons to do with the remaining mass of cast iron: a reduced mass leads to high temperatures. Lastly, for mere geometrical reasons: in fact if, with time, the pads wear down and the disc is allowed to fall below its minimum thickness, then the serious consequences noted below will occur. First of all the piston's **dust-shield** may tear. This does not create an immediate danger, but in the case of dirty and muddy conditions, abrasive powders rapidly damage the **gaskets** which in turn affects the air-tightness of the fluid circuit.



Worn disc / worn pads.

In certain cases the **pads** may no longer be guided and come out of their seat. In such cases braking action will quickly deteriorate or, even worse, not exist at all. If the **piston's** position is too advanced it can be ripped out of the caliper on the effect of torsion movement. When this happens the vehicle will no longer brake! Whenever pads are replaced it is important to ensure that the disc will not fall below minimum thickness during the life of the new pads.

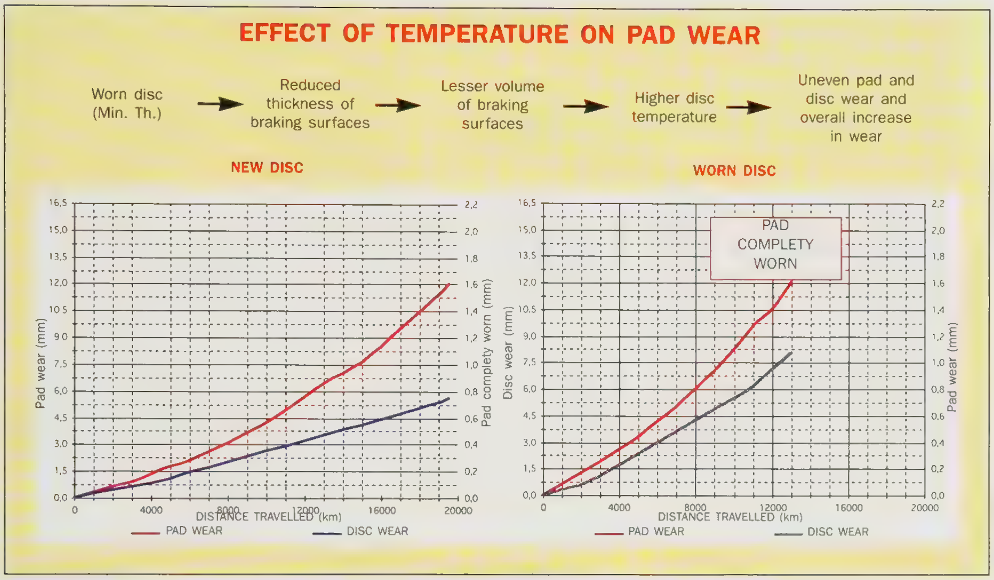
An important consequence of



Heavily worn disc and pads.

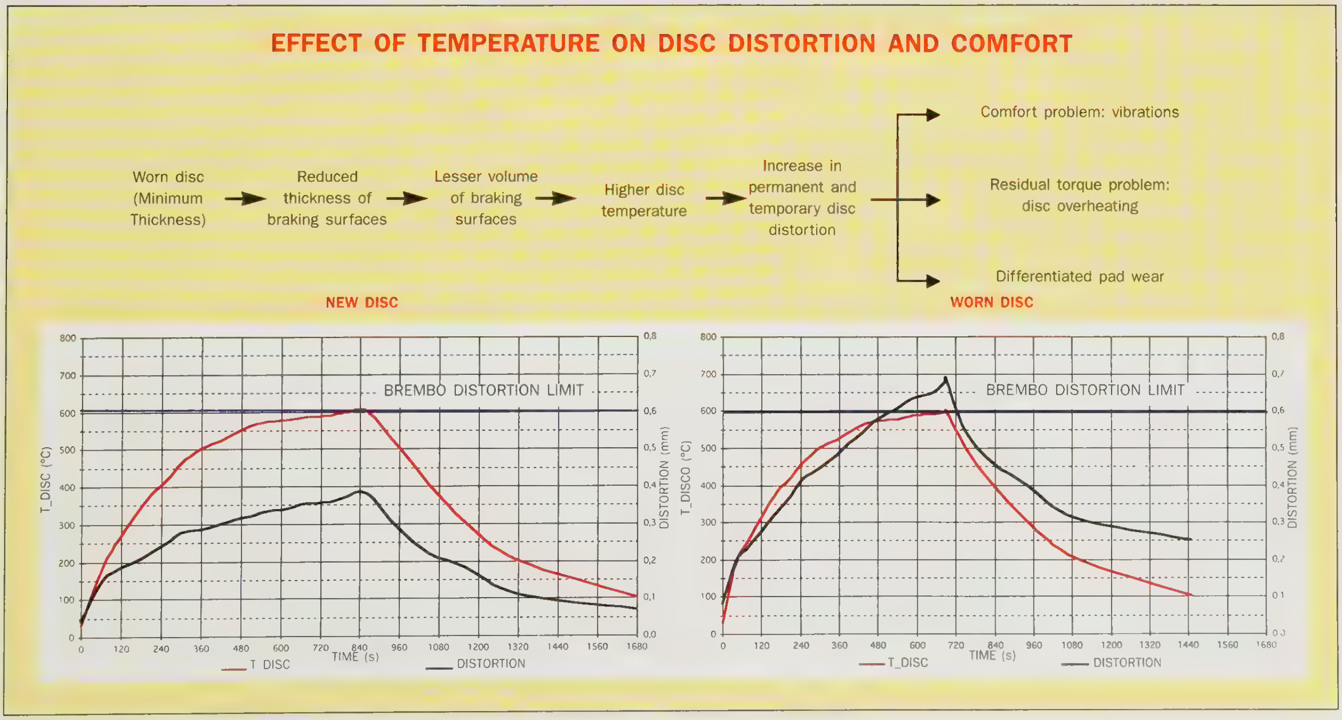
3.2.2

Pad wear / disc wear. (Min. Th.)



wear - and, therefore, of the reduction in the disc's thickness - is the temperature increase reached in two identical instances of braking from the point of view of the pressure applied. Above all the volume of cast iron is less in as much as the disc's thickness is minimal and, given an equal energy transmission, the temperature of the braking surfaces is higher.

Distortion temperature.

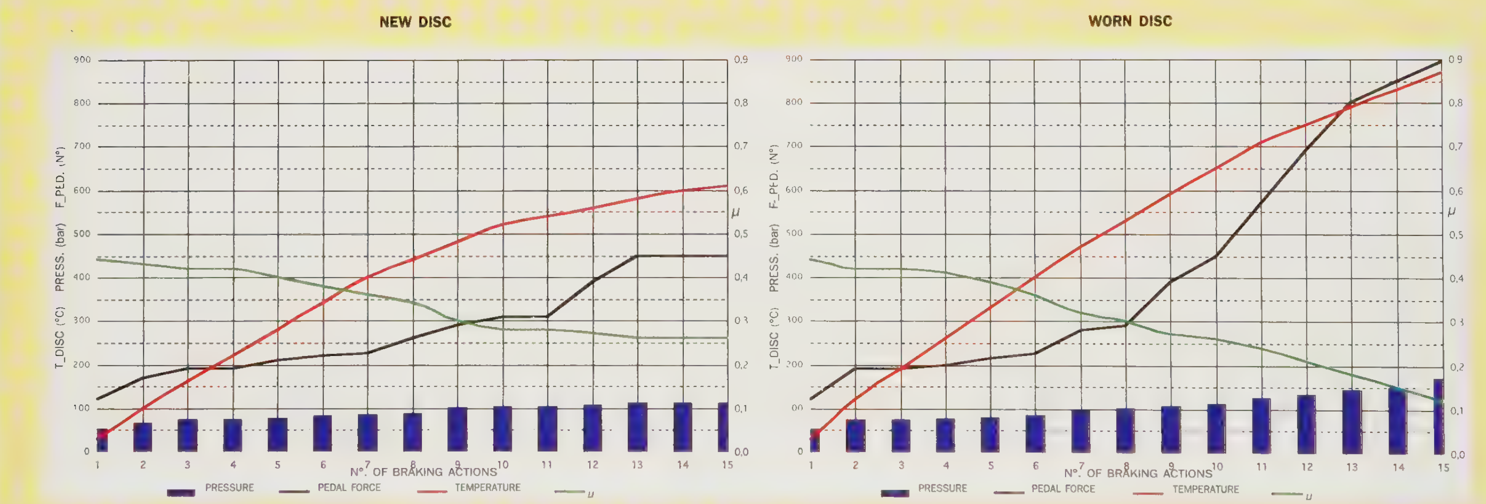


3.2.2 Under equal test conditions it is interesting to compare respective **wear** measured for a new disc/pad combination and wear found when the pads are new but the disc has reached minimum thickness. It can be noted that with the worn disc the **pads** show wear after a 30% shorter distance when compared to a disc of original thickness. This phenomenon is even more serious as far as the **disc** is concerned.

It is also possible to compare the **temperatures** reached in a brake equipped with a new disc and, for the same brake, with a used disc. The test consists of performing a series of braking actions in rather rapid succession so that the temperature increases smoothly. The lower volume for the braking surface areas causes quite a rapid increase in temperature. Due to dilation the disc distorts and begins to **run out**. As this happens more often in the case of used discs, brake pad wear is uneven and comfort decreases. Such distortion may

TEMPERATURE INCREASE TEST - ONSET OF FADING

Braking at constant deceleration and with a constant interval between two braking actions

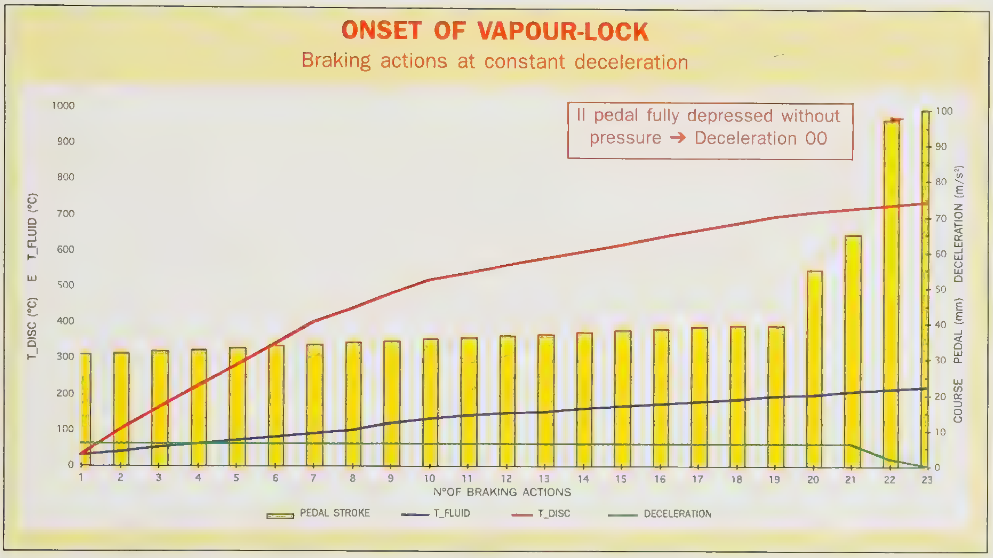


Fading. become permanent and compromise the correct functioning of the braking system.

Again in tests under the above conditions, a more rapid onset of **fading** - namely, the reduction of friction coefficient at high temperatures - can be noted. In this case too, the test consists of a series of braking actions performed at constant deceleration and at equally spaced time intervals. It can be observed that a progressively higher pressure is required to reach a given deceleration level. The same can be said for the force that needs to be applied to the brake pedal.

In a similar test, but involving a greater number of braking actions, it can be observed that there is a considerable increase in pedal slack at the end of the test.

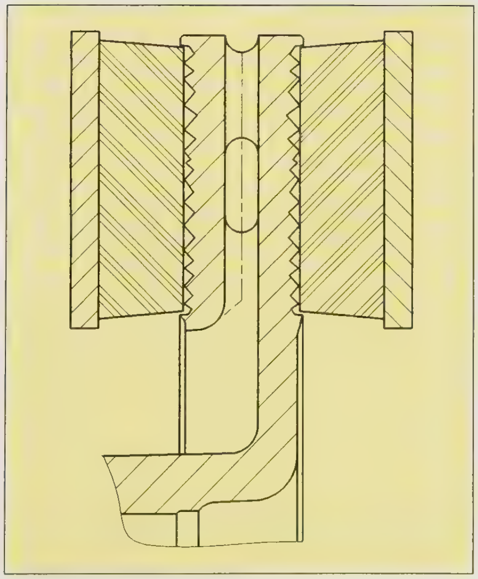
In fact the **fluid temperature** exceeds 200°C leading to the early appearance of **vapour-lock**. 3.2.2



Vapour-lock.

3.2.3 WEAR AND COMFORT

Apart from instances of wear that directly affect safety, those affecting comfort must also be considered. For example, not only the presence of scores and grooves but also cases of uneven wear - including oblique pad wear or any other type of uneven wear. Generally speaking, such instances are not the result of normal wear. When they arise their origin must be analysed very carefully. There may also be uneven disc wear. For instance, examination of the braking surface profile may indicate curving and a considerable variance in thickness (DTV). The disc vibrates and the effect of this can be felt at the brake pedal and steering wheel levels. There may even be acoustic emissions. In order to analyse such instances in a more technical manner, the torque can be measured during braking at constant deceleration: very heavy vibrations can be noted in the case of a worn disc.

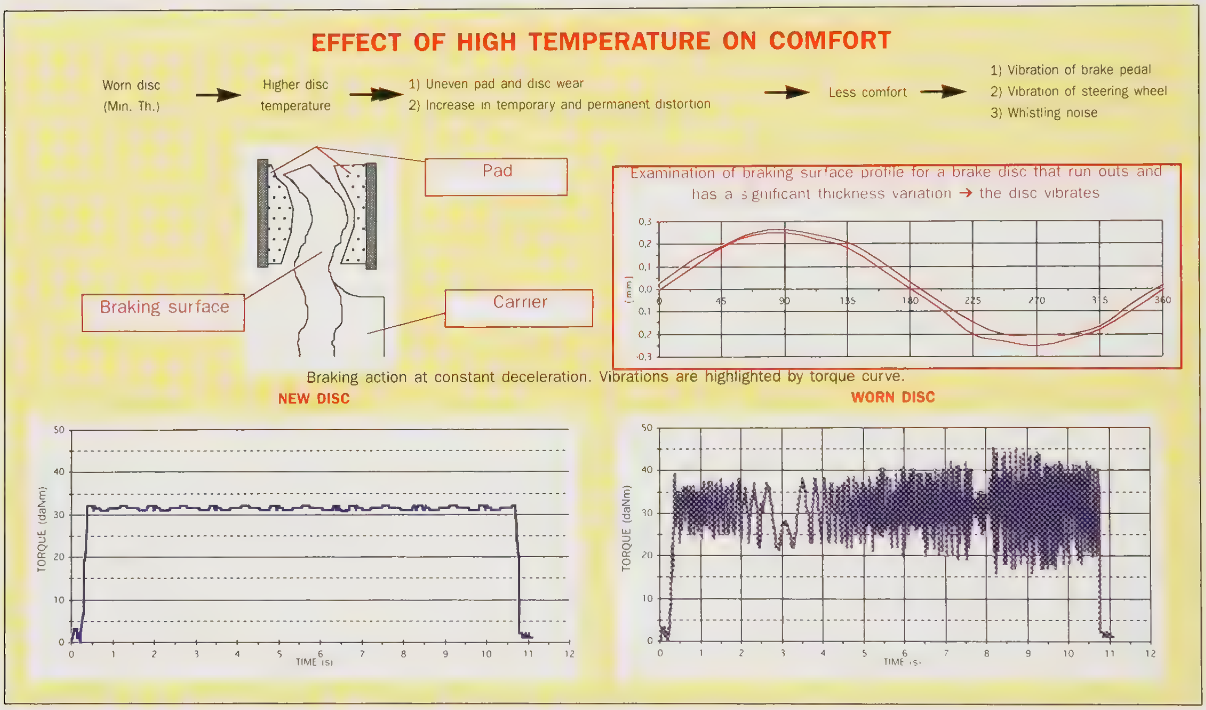


New pads fitted with a heavily scored disc.

3.2.3

By the same token, if new pads are fitted and the disc is heavily scored (0.5 mm) the pedal will be "spongy" and running-in difficult. There is also every possibility of both vibrations and whistling noises.

Uneven wear and vibrations.



3.3 REPLACING A DISC

In the previous sections we have reviewed problems arising out of disc deterioration. We have also emphasised the fact that the majority of such problems must lead us to reflect on the state of the braking system, its origin and its use... Certain of these **questions** concern brake maintenance and, in particular, the care taken when replacing pads and discs.

The first observation regards the **personnel** who perform such maintenance operations. Clearly they must be skilled and have undergone specific training on the subject of brake component and, above all, disc replacement. Their knowledge needs to be refreshed and, from time to time, should be completely updated in training courses.

The second important, indeed mandatory requirement is that the **installation instructions** must be available, read and followed.

The third observation, already mentioned before, is that the pads and discs that are removed are an important **source of information**. For instance, the state of the disc must be observed carefully (state of braking surfaces, colour, profile). This examination can highlight faults in the func-

3.3

tioning of one or more components (calipers, pads, bearings, etc.). It is important to resolve such problems before replacing the disc.

When do brake discs need to be replaced? We will summarise the various reasons already mentioned:

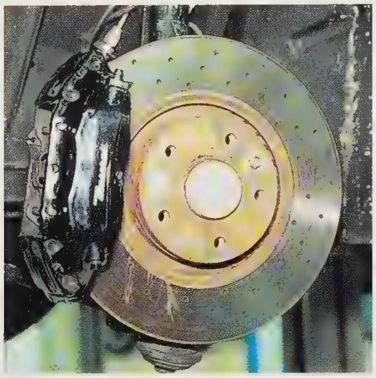
- When, during the course of a normal check, it is found that the disc's thickness is less than or has reached the **minimum thickness** indicated on the outer rim of the disc itself (**MIN**imum **TH**ickness).
- When, while checking or replacing pads, **cracks** longer than 30 mm are found.
- When circular score marks are observed, deeper than 0.3-0.4 mm.
- When **dark patches** are found on the disc's surface.
- When, after a check, measurements reveal **distortion** or noticeable variations in height between a number of points over the disc's braking surfaces.

Lastly, before moving on to practical issues, we should bear in mind the following general rules:

- **Instructions for the replacement of components should be read and scrupulously followed.**
- **Both discs on the same axle must be replaced on the same occasion.**
- **Make sure that the disc reference number corresponds to the vehicle on which it is to be installed. The same goes for the pads.**
- **Install two discs from the same pack (from the same production batch).**
- **Pads must always be replaced when discs are replaced.**

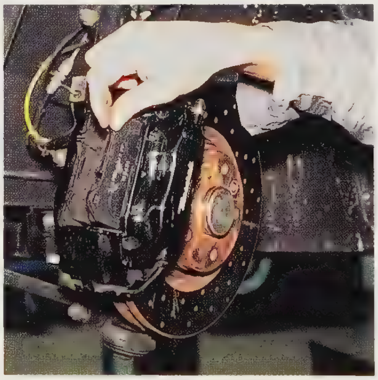
3.3.1

3.3.1 DISMANTLING AND REFITTING

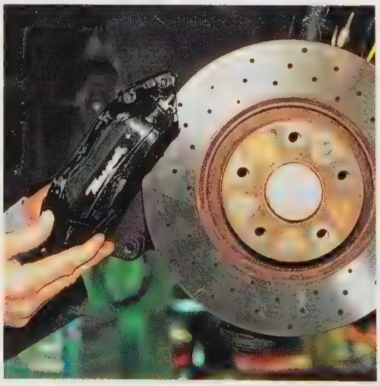


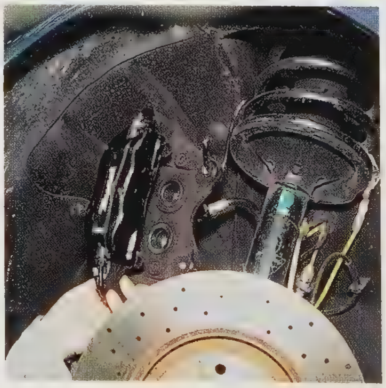
1) Remove the wheel.

2) Remove the pads and push back the pistons using the proper tool for this operation.



3) Dismantle the complete caliper from its support, without disconnecting the brake fluid ducts. Do not leave the caliper hanging from the flexible ducts. Suspend the caliper in some way (for instance, on a hook).





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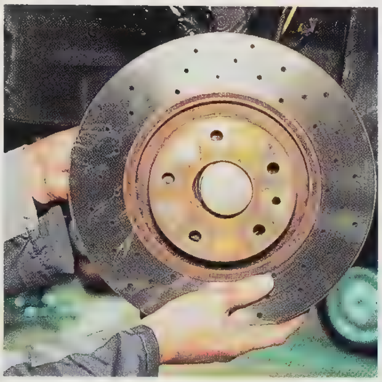
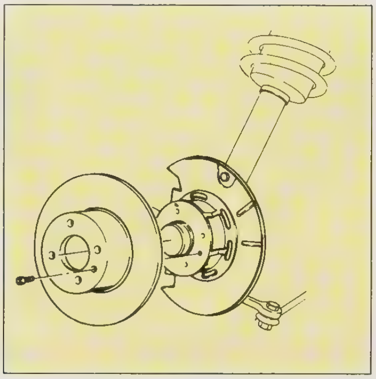
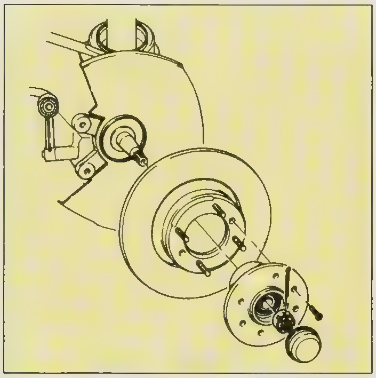
4a) Dismantle only the used disc, if this has a mounting flange inside the carrier.





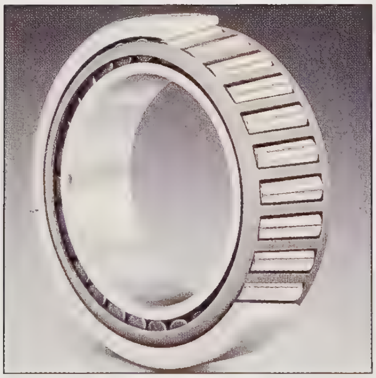
4b) If the mounting flange is external to the carrier then it will be necessary to first dismantle the hub and thèn the worn disc.



5) Clean the new disc with an appropriate solvent (for example, petrol or spirit). The anti-corrosion layer must be completely removed. The disc must not be contaminated by oil or grease as these substances could be passed on to the pads and so reduce their performance. Carefully clean the surface of the disc that will come into contact with the hub.

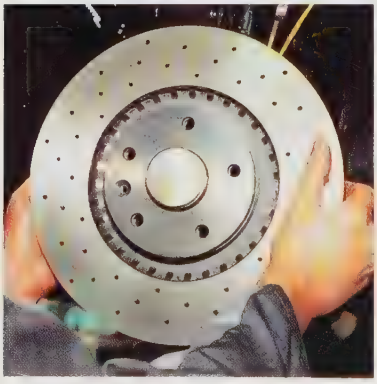
3.3.1

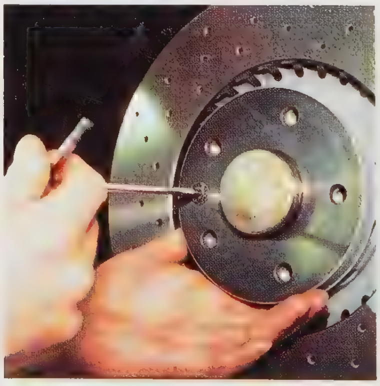
6) Carefully clean the surface of the wheel hub on which the disc will be installed. Eliminate rust and other deposits. Check that the support surface is neither distorted nor damaged.



7) Check that play in the bearings does not exceed the tolerance and that the ball bearings rotate freely within their crown. If possible, adjust the bearing.

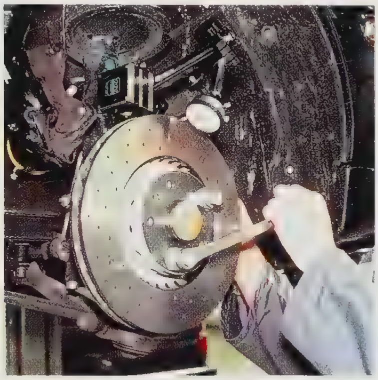
8) Fit the brake disc on the hub.

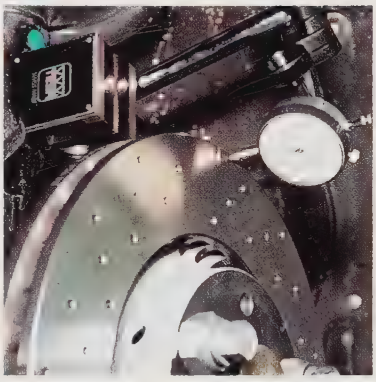




3.3.1

9) For discs with a mounting surface that is external to the carrier, fit the wheel hub and adjust the wheel bearing.



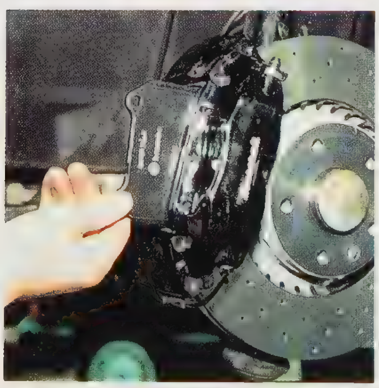


10) Once the disc has been fitted, use a DTI Gauge (fixed to the suspension bracket) to measure disc run out on a braking surface at the point of its external diameter. At the end of one complete rotation, run out should not exceed 0.10 mm. If it is greater, change the position of the disc on the hub (provided that the mounting aperture allows this), or fit the second disc from the pack. If the disc is held in place by one bolt only, secure it to the wheel hub by two other bolts (using wheel studs plus washers to compensate for the thickness of the wheel) in order to simulate rotation conditions once the wheel has been fitted.
Measurement of disc run out is a vitally important operation: if there should be too much run out then in time, after a few thousand kilometres, the disc may be subject to abnormal wear when travelling - and outside of occasions when the brakes are applied (due to slight rubbing against the pads) - and braking vibrations may occur.
The recommended maximum tolerance for disc run out has been established on the basis of our experience. Other sources may indicate slightly different values - in such cases the original value should be observed.

3.3.1

11) When the maximum recommended run out for the disc is exceeded then check run out for the bare hub. It should be borne in mind that the value recorded for the hub will double when measured at the outer diameter of the disc.

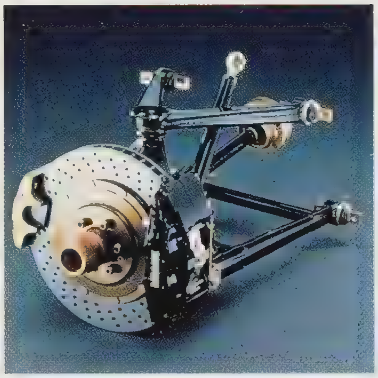
12) Fit the caliper to its support. A floating caliper must move smoothly and regularly along its guides. The pistons must move freely. Dust shields must be integral.



13) Fit the new pads - they must be free within their seats. Fit the springs and any other parts included in the kit.

14) Before fitting the wheel make sure that the rims are not distorted.
Balance the wheel/tyre unit correctly. Tighten bolts in the correct sequence and observe the recommended torque.

15) Check that the elements comprising the suspension are integral.
Check that the shock absorbers function properly. The suspension adjustment must correspond to the manufacturer's recommended values.



3.3.2

3.3.2 TESTING AND RUNNING IN

Once the discs and pads have been replaced, the mechanic should then carry out a **road test**. He must ascertain that there are no brake vibrations or noises, either while travelling or during braking. He must also check that the braking action is both correct and efficient, even though the brakes are not yet run in. It is the braking distance that is important. Never brake sharply during these tests.
The car user should be advised to observe an approximately **200 km** running-in period. During this period a short, smooth braking action should be adopted so that the pads can align correctly to the disc surface. Too sharp or heavy braking may not only cause the pads' friction material to overheat, but also the disc itself. This would end up by compromising brake integrity and performance. In particular, do not attempt to activate the ABS.

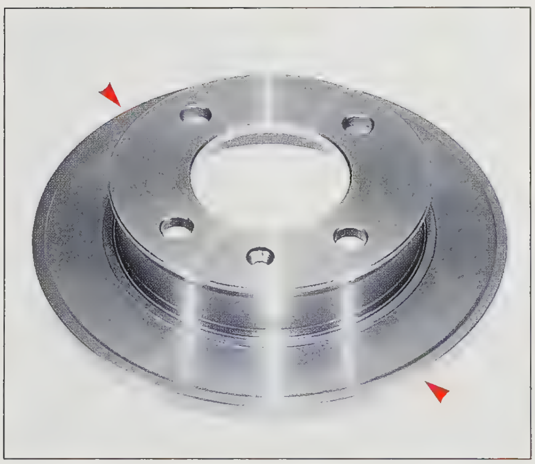
Chapter 4

CAUSES AND CONSEQUENCES OF DISC DETERIORATION: PRACTICAL EXAMPLES

In the previous chapters we have examined, albeit sometimes from a theoretical standpoint, the various types of alteration and deterioration that can affect a disc. These can be summarised by classifying them in four groups:

- **Geometrical modifications** that can be measured quite easily using a sliding caliper, a micrometer caliper or a DTI Gauge.
- **Structural modifications** that can be observed by examining the disc's braking surface. Simple, unaided observation will be sufficient in cases involving a change in colour whereas in other instances a microscope will have to be used.
- **Wear**, or rather types of wear, since the causes and effects can be many.
- **Cracks** that may lead to **breakage**.

We have also described - without going into too much detail - the main deterioration **mechanisms** that involve stresses of both a thermal and mechanical origin.



When describing disc **production** we reviewed the various defects that might arise were the production process not properly controlled: run out, DTV, incorrect planarity, equilibrium defect, but also an inappropriate or irregular composition of the cast iron.

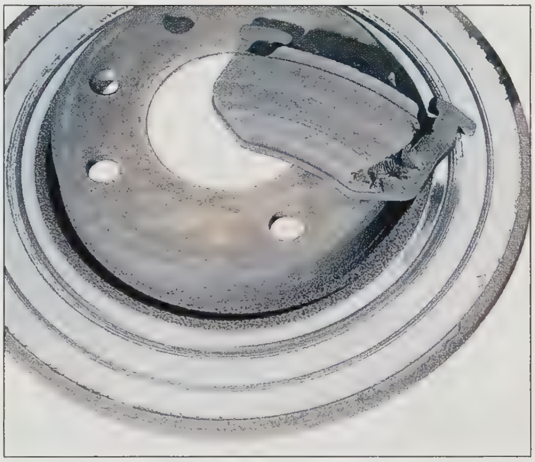
In this chapter we will avoid re-examining the consequences of these imperfections since current quality controls ensure that braking problems due to defective manufacture are extremely rare, in the order of a few tenths of one percent. On the contrary, we will conduct a review using a very practical approach as regards the various defects and deterioration caused by **use**. The word *use* is intended in a broad sense since it also includes disc **installation**, braking in **extreme conditions**, **excessive wear** and the involvement of **other components** in the braking system.

Examination of the different cases of disc deterioration shows that the majority of these could have been avoided if greater care had been taken during the installation stage.

This not only concerns certain checks that can be quantified by means of measurement but also, in a more simple manner, by a close visual examination of the components concerned. By way of example, and before attempting to classify the

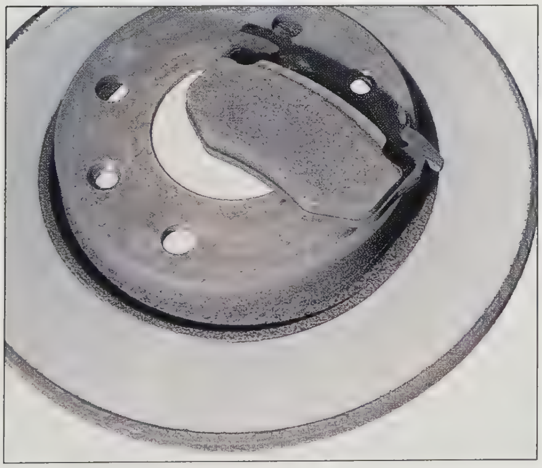
various causes of deterioration, here are two pertinent cases. As these are extreme and rather infrequent cases they have been excluded from the more recurrent situations in the list.

In the first case the **hub is distorted** or presents a **conspicuous run out**, probably as a result of a collision. The disc has been fitted without first repairing this damage. Such an assembly will progressively cause an increase in braking vibrations. If the run out is particularly pronounced then these vibrations may well be felt right from the very first braking action. The illustrations show the disc, in an oblique position, with an uneven wear first on one side and then, half a turn later, on the other. Visual examination or the use of a DTI Gauge highlights possible anomalies during fitting.



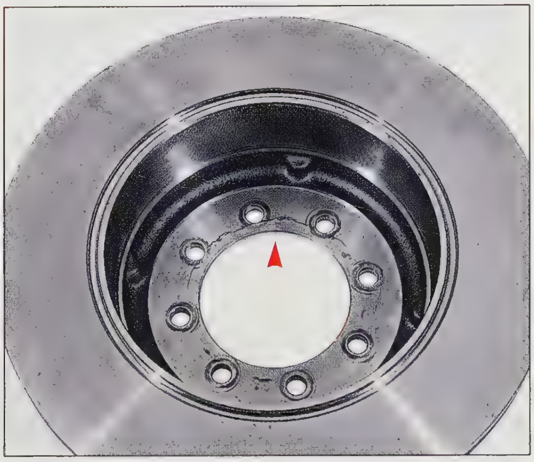
This examination, suggested here in order to establish poor functioning, is even more useful during fitting as a means to ensure that the braking system is operative.

The second case is exceptional, rather extreme. Careful examination of the state of the disc and pads reveals visible defects and is always a valuable source of information as to the overall functioning of the system. It can be seen in the photo that a foreign body (a screw) is lodged between the disc and pad, it probably happened during refitting. The illustration shows the damage that this piece of steel can provoke, damaging the disc and causing unusual wear, a source of vibrations and noise when braking.



4.1

4.1 DETERIORATION DUE TO FITTING THE DISC

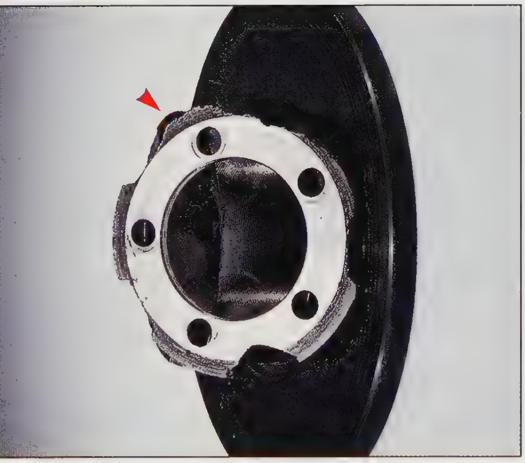


4.1.1 INCORRECT TIGHTENING

Description of defect: Formation of cracks on the carrier surface in contact with the hub. This is due to incorrect tightening during fitting. The tightening sequence has not been followed and torque is insufficient. Failure to follow the recommended sequence and tightening torque can cause distortion of the carrier mounting surface even when there are no visible cracks.

Consequences: Distortion of the carrier mounting surface causes vibrations that can be felt immediately after fitting when the brake pedal is pressed.

Advice: Fit another disc, following the recommended sequence and tightening torque.

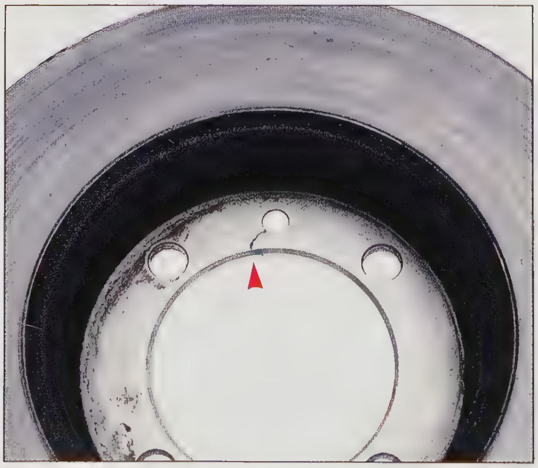


4.1.2 FAILURE TO OBSERVE THE RECOMMENDED TIGHTENING TORQUE

Description of the defect: The carrier mounting surface breaks away from the rest of the disc. There are clear signs of excessive tightening, above all in the area of the two fixing holes. This is evidence of a failure to observe the recommended torque and sequence during tightening.

Consequences: Pronounced rasping noises and absence of braking torque.

Advice: Fit another disc, following the recommended sequence and tightening torque.



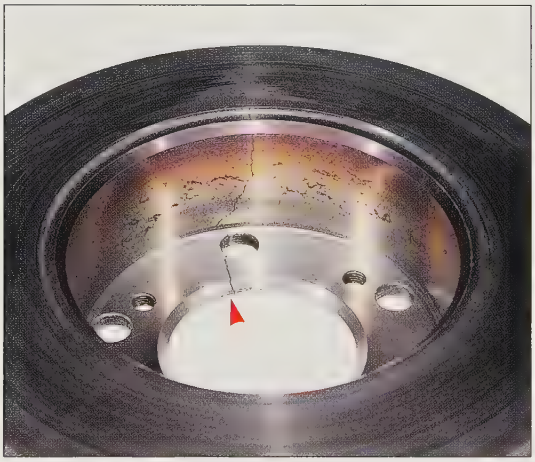
4.1.3 EXCESSIVE TIGHTENING OF THE POSITIONING BOLT

Description of the defect: The carrier mounting surface can easily distort when the disc positioning bolt is tightened too much. This excessive tightening can cause the mounting surface to break as can be seen in the photo.

Consequences: Run outing cannot be kept within an acceptable tolerance. Heavy vibrations occur dur-

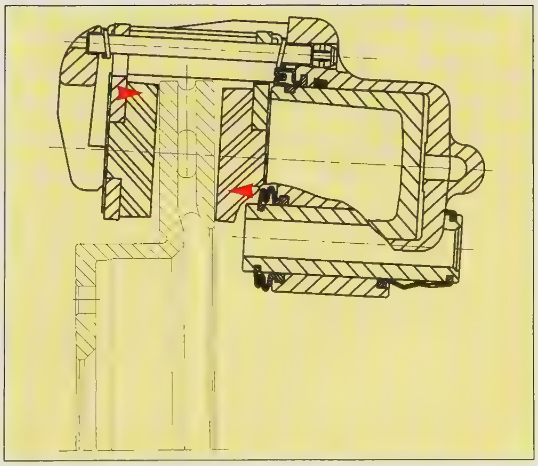
ing the very first kilometres following installation.
Advice: Tightening bolts are only intended to ensure that discs are positioned correctly. Do not tighten them excessively.

4.1.4 FITTING A DISC THAT DOES NOT CORRESPOND TO THE CAR



Description of the defect: Formation of cracks on the carrier mounting surface. Signs of a poor match between the diameter of the disc centring and that of the hub.
Consequences: Disc contact with the wheel hub is incorrect. This defective installation will immediately cause vibrations due to excessive run outing.
Advice: Check catalogues to determine the correct disc reference: model, year of manufacture. Never force discs when fitting.

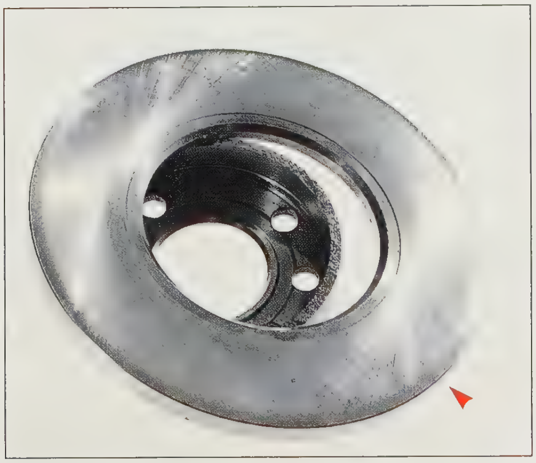
4.1.5 INCORRECT ASSEMBLY OF THE CALIPER BODY ON THE AXLE

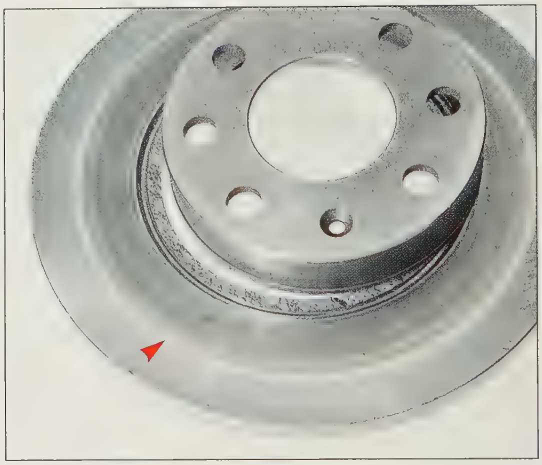


Description of defect: The braking surfaces have broken away from the hub. Asymmetrical braking surface wear can be noted: the central area of the external surface in respect of the vehicle and the outer edge of the internal surface. In this case mechanical stress has caused the disc to break and the braking surfaces have come away.
Consequences: The impact of this breakage can be felt when braking. Very loud rasping noises. Safety is compromised.

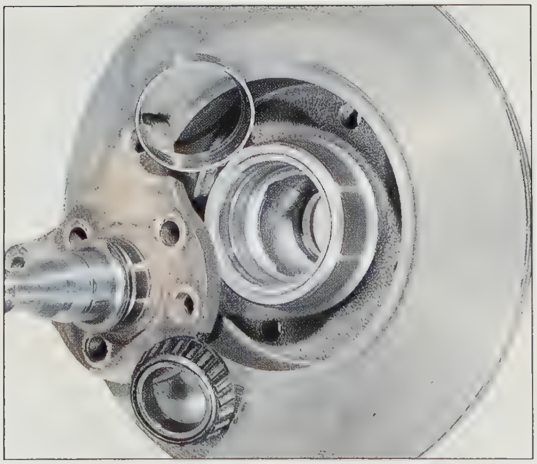
4.1.6

Advice: Before fitting new discs check the alignment and assembly of the caliper body on the axle.





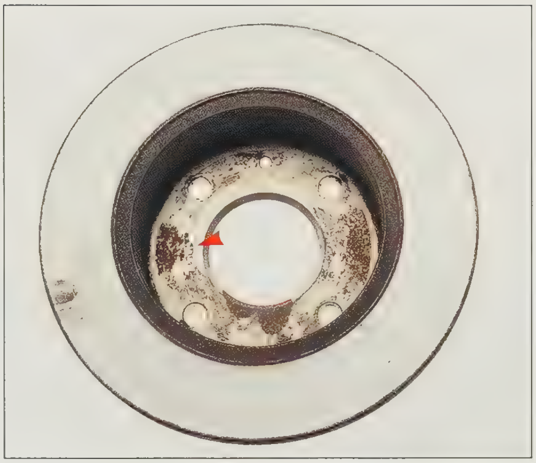
4.1.6 INCORRECT TIGHTENING OF THE DISC AND HUB BEARINGS



Description of defect: An exaggerated tightening torque knocks the bottom out of the bearing seat.
Consequences: Braking system functioning is compromised because of disc instability relative to the bearings. Strong vibrations are felt right from the first braking action.
Advice: Replace the hub, bearings and disc. Apply correct tightening torque when installing.

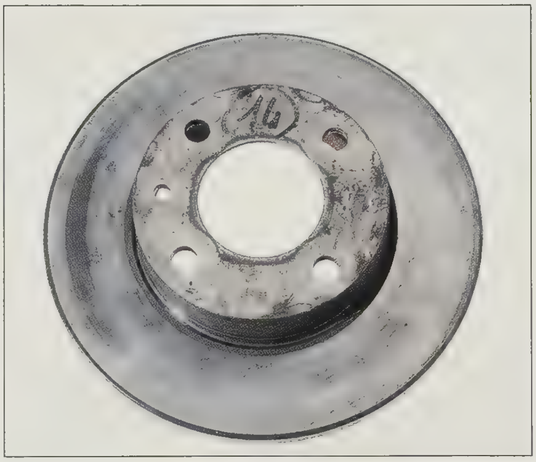
4.1.7 DIRTY HUB

Description of defect: The hub surface was not cleaned when the disc was fitted: presence of rust or dirt. Tightening against this unsuitable surface causes the new disc to run out excessively.
Consequences: This error during installation causes the onset of vibrations after

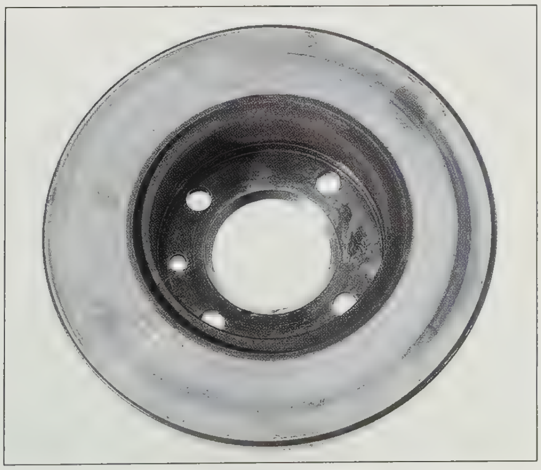


a few hundred or thousand braking actions, vibrations that increase with the distance travelled. Uneven disc wear as a result of the pads causes DTV to increase - this is the origin of the vibrations - and noise (see section 3.3.3).
Advice: Clean contact surfaces very carefully. Check disc run out after installation.

4.1.8 PRONOUNCED WHEEL HUB RUN OUT



Description of defect: Excessive hub run out causes the braking surfaces to wear as they are not parallel to the plane of the disc. Evidence of localised overheating is indicated by the darker colour of the worn areas. This is due to an alternating rubbing action of the disc and pads as a result of pronounced wheel hub run out.
Consequences: Vibrations can be felt right from the start and progressively increase. Onset of loud noises.
Advice: Check the wheel hub run out and ensure that this falls within the tolerance specified in the disc installation instructions.



4.2

4.2 DETERIORATION DUE TO USE

4.2.1 NO RUNNING IN

Description of defect: Disc shows colouring of varying intensity and shades (blue, violet, golden), mainly visible in the cooling areas (groove and carrier interior).

Consequences: Initial slight vibrations that progressively increase. Overheating of this type alters the mechanical characteristics of the cast iron in as much as there is a change in structure due to the formation of cementite (**Fe_3C**).

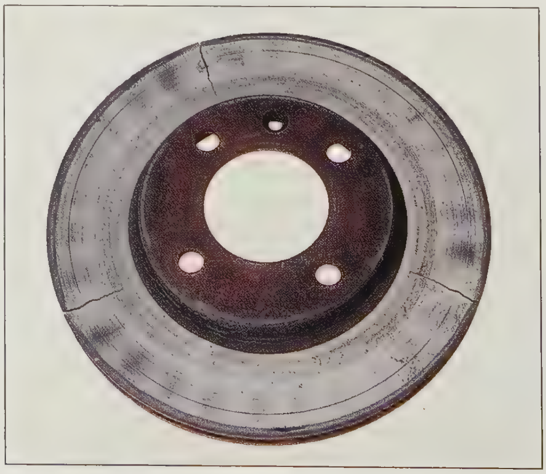
Advice: Always advise users to observe a running in period. Brake only moderately and briefly during the first 200-300 kilometres over a mixed itinerary. Avoid prolonged pad to disc contact.

4.2.2 INTENSIVE USE

Description of defect: Disc thickness is considerably less than the recommended minimum thickness (4 mm less in total). Cracks are evident. Heat spots are visible in areas corresponding to the ventilation blades. This is advance warning that other cracks will form.

Consequences: Noises, vibrations.

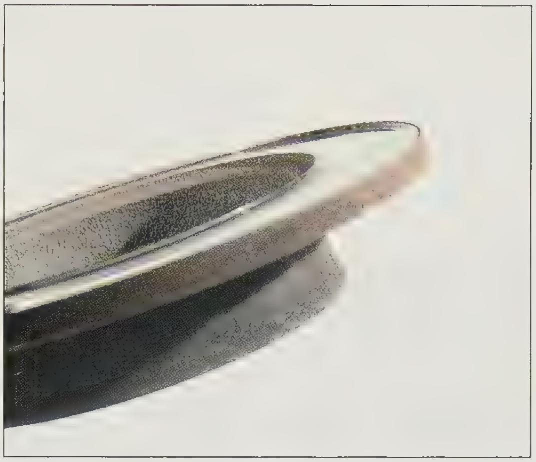
Advice: This situation is typical of that found on certain sports vehicles which are subjected to an intensive and excessive use on the road.



4.3

4.3 EXCESSIVE WEAR

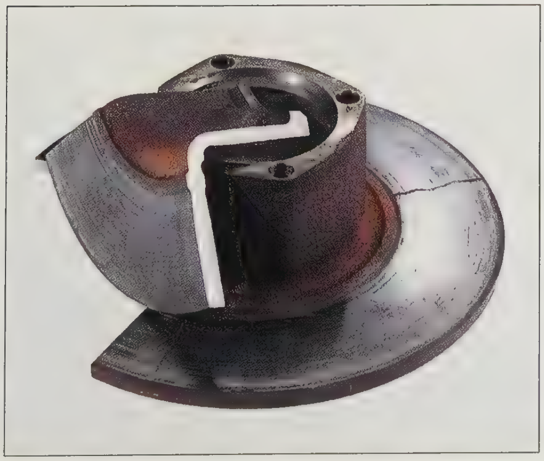
4.3.1 EXCEEDING THE LIMIT



Description of defect: The thickness of the braking surfaces measured using a micrometer is less than the recommended minimum thickness etched on the outer disc rim or on the carrier.
Consequences: Performance and comfort decreases.
Advice: Check state of disc wear periodically. The disc should be replaced after every two or three pad changes. Pads must be changed every time discs are replaced.

4.3.2 EXCESSIVE WEAR WITH CRACKS

Description of defect:
a) disc
The minimum thickness indicated on the outer rim of the disc has been exceeded by more than 1 mm. Furthermore, the disc has been subjected to excessive operating temperatures as a result of the reduced braking surface thickness. This causes cracks of a thermal origin.
b) pads
More marked wear can be noted in the central area of the disc whereas the area in correspondence with the pads is less worn. This can be attributed to the presence of hard points in the friction material, an indication that the production mixture was not homogeneous. It can also indicate poor functioning of the caliper.



Consequences: Distortion caused by vibrations during braking. In the long run cracks may form that can lead to disc breakage.

4.3.3

Advice: Periodically check disc wear. The disc must be replaced every two or three pad changes.

4.3.3 APPEARANCE OF CRACKS

Description of defect: The disc has been subjected to excessive operating temperatures: in the outer area of the braking surface there are evident signs of overheating. High operating temperatures lead to the appearance of cracks.
Consequences: Distortion and pad "bouncing" when hot that causes vibrations during braking. With time, cracks form and the disc may break.
Advice: The worn disc must be replaced. Check the state of wear periodically.

4.3.4 EXCESSIVE WEAR AND PADS COMPLETELY WORN DOWN

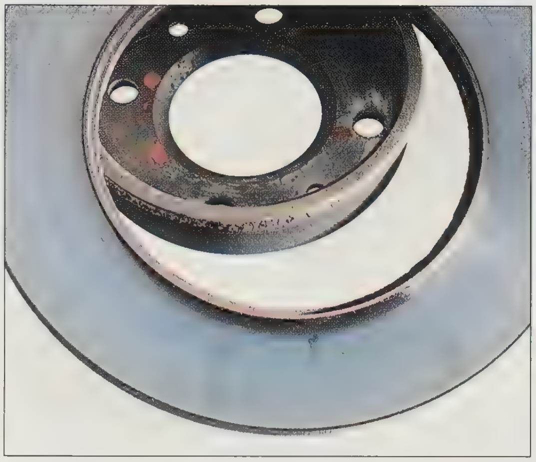
Description of defect: The disc is extremely worn and has been damaged by the metal pad support, the friction material of which has completely disappeared. The thickness of this disc when new was 7 mm, measured now it is 3.5 mm compared to a recommended minimum thickness of 5 mm.
Consequences: Very loud noises, very long braking distances, caliper functioning is critical.
Advice: Replace pads when they reach wear limits. Check out the pad wear warning indicator circuit.

4.3.5 BREAKAGE DUE TO EXCESSIVE WEAR

Description of defect: Braking surfaces show evident signs of overheating due to the considerably reduced mass of the worn disc. This situation has caused the braking surfaces to break away from the hub.

Consequences: Violent impact during braking. A very strong rasping noise when braking. Possible safety problem.

Advice: Always check the disc thickness every time the pads are replaced. Replace the disc before it reaches its wear limit.

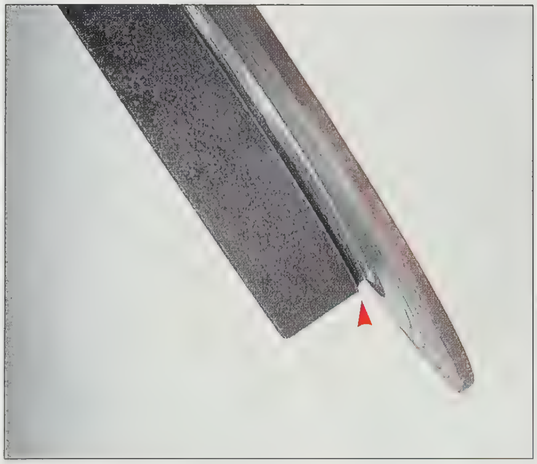


4.3.6 EXCESSIVE PAD WEAR AND MOVEMENT OF THE SUPPORT

Description of defect: Disc thickness less than the limit value. The disc has been worn by the pad support as friction material is completely absent. The metal support plate has come out of its seat in the caliper and has almost entirely cut the disc brake surface from the carrier. The braking surfaces are near to breaking away from the carrier.

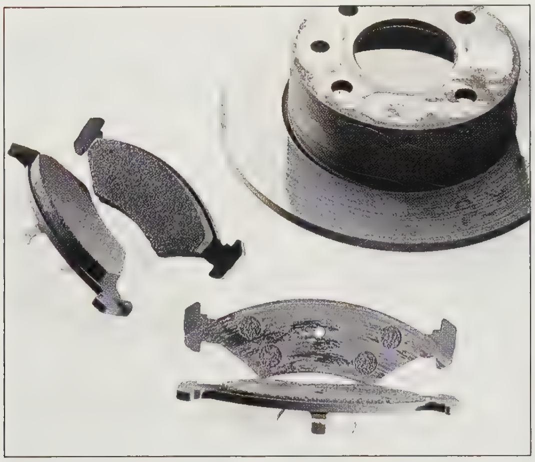
Consequences: Rasping noises, loss of efficiency (considerable brake pedal slack), possible rubbing between the disc and caliper, thrust of the caliper is not symmetrical.

Advice: Check and, if necessary, repair the caliper. Replace the discs and pads.



4.4 DETERIORATION DUE TO OTHER BRAKING SYSTEM COMPONENTS

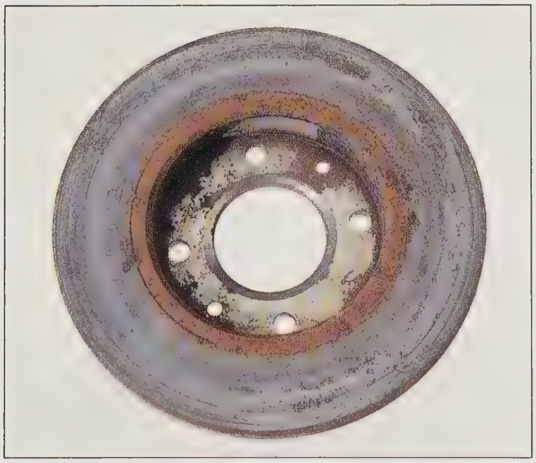
4.4.1 UNEVEN WEAR OF VARIOUS PARTS



Description of defect: A braking surface of one of the discs is in contact with the metal pad support. Examining the pads it is noted that wear is uneven due to blocking of the caliper (the pads on the other caliper are in perfect condition).

Consequences: The caliper's two pads are completely worn down with consequent onset of noises and vibrations, the brake pedal has to be depressed completely. Braking distance is very long.

Advice: Check, repair or replace the caliper. Replace all discs and pads.

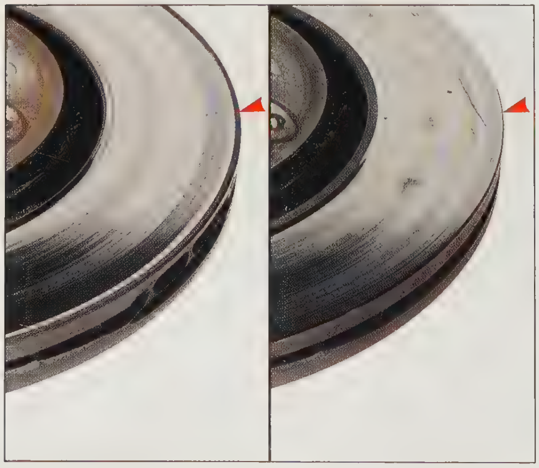


4.4.2 VITRIFIED DISC

Description of defect: Presence of a very fine deposit of friction material on the disc surface which now has a shiny finish (corrosion has then caused the detachment of part of this layer).

Consequences: Loss of braking efficiency, braking distances too long. The pedal is very stiff but with no braking action.

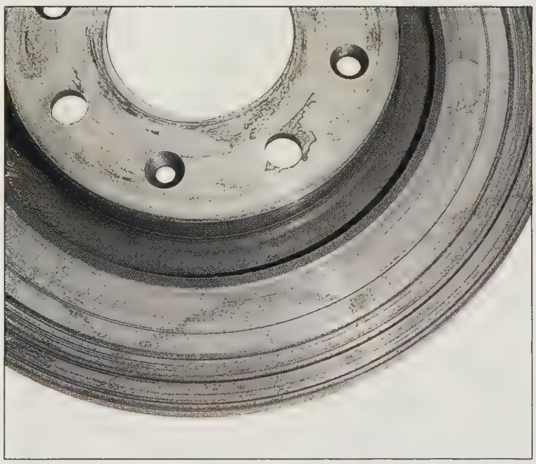
Advice: Replace discs and pads. Use high, original, quality pads.



4.4.3 UNEVEN BRAKING SURFACE WEAR

Description of defect: The two pads were not positioned in the same manner with respect to the disc. Wear has not been the same for both surfaces. Heat spots can be noted at the centre of the braking surface due to high thermal exposure. The caliper and/or the pads were not fitted properly.

Consequences: Gradual onset of vibrations due to the heat spots. Possible appearance of cracks.
Advice: Check and, if necessary, repair the calipers. Check the pad model and friction material quality.

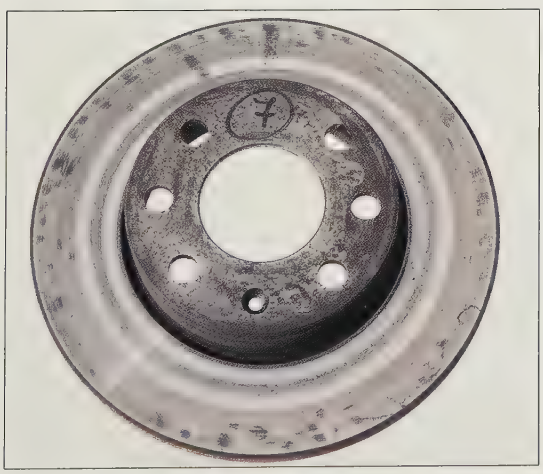


4.4.4 DEEP GROOVES AND SCORING

Description of defect: Deep scores caused by penetration of foreign bodies between pads and disc can be noted. This can be due to unsuitable pad material or the presence of badly distributed abrasives in the mixture.
Consequences: Very unpleasant noise both during braking and when travelling. Diminished efficiency as a result of the reduced contact surface between disc and pads.
Advice: Replace discs and pads.

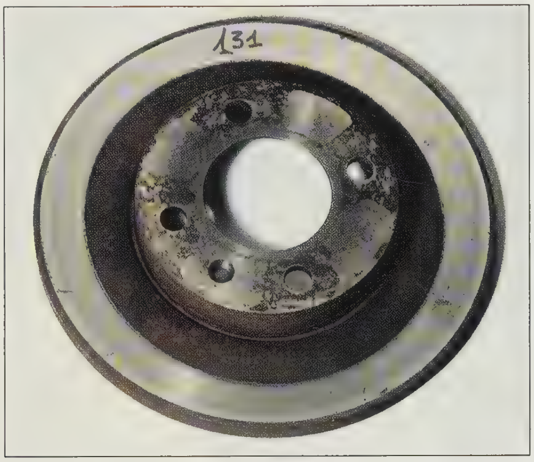
4.4.5 FRICTION MATERIAL DEPOSITS

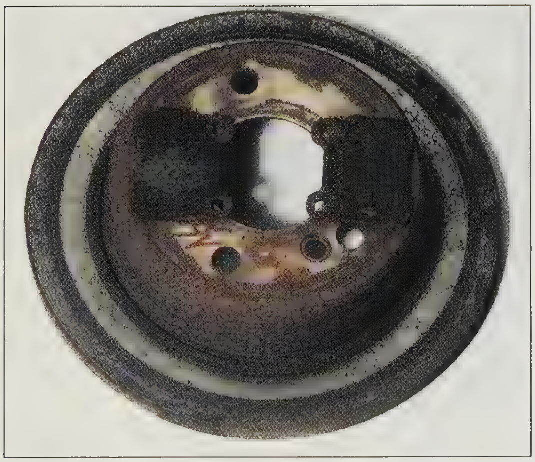
Description of defect: The braking surfaces are completely covered by very dark spots. These spots are due to deposits of pad friction material. This causes overheating which in turn leads to a transformation of the cast iron with the formation of very hard cementite.

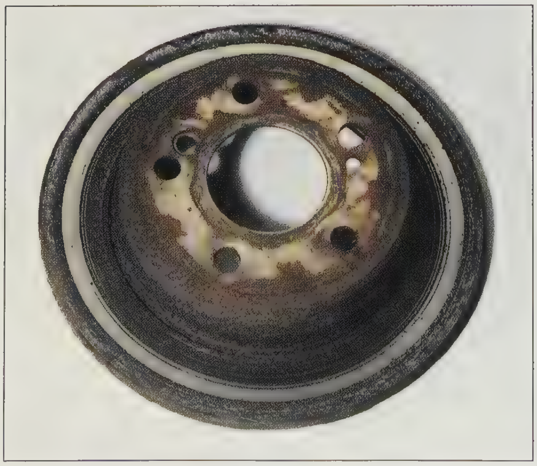


Consequences: Onset of vibrations that become progressively worse.
Advice: Only install friction material that is suited to the brake and vehicle.

4.4.6







4.4.6 BRAKING SURFACES PARTLY WORN BY THE PADS

Description of defect: The braking surface only shows wear in the outer area. The inner area never comes into contact with the pads as indicated by the presence of corrosion (rust). This situation could be caused by:

- incorrect installation of the caliper and hence the pad which does not make full contact with the disc
- loss of part of the friction material
- fitting of wrong pads

Consequences: Reduced braking torque. Increase in operating temperature as the surface on which the pad works is reduced (by about 50% in this example) compared to its normal working surface. There is a risk of localised overheating and therefore the onset of hot judder-type vibrations. Moreover, reduced system efficiency leads to high stress levels and therefore rapid and/or uneven wear (cold judder).
Advice: check the installation and correct functioning of the caliper. Check the fitting and condition of the pads. Check that the pad model is suitable for the particular vehicle.

4.4.7 PARTIALLY WORN AND VITRIFIED BRAKING SURFACES

Description of defect: This disc shows a deterioration that is the sum of defects described in 4.4.2 and 4.4.6 above. In this case the pad only acts on the inner section of the braking surface. High stress has led to overheating, vitrification (deposit) and detachment of friction material.
Consequences: Progressive reduction in efficiency of the system and, when friction material detaches, total inefficiency of the system.
Advice: As for 4.4.2 and 4.4.6.

4.4.8 CURVED PADS

Description of defect: The pads only act on the central section of the braking surface. They may be curved.
Consequences: Reduced braking action with the consequences described in points 4.4.6 and 4.4.7.
Advice: Check pad planarity and the functioning of the calipers.

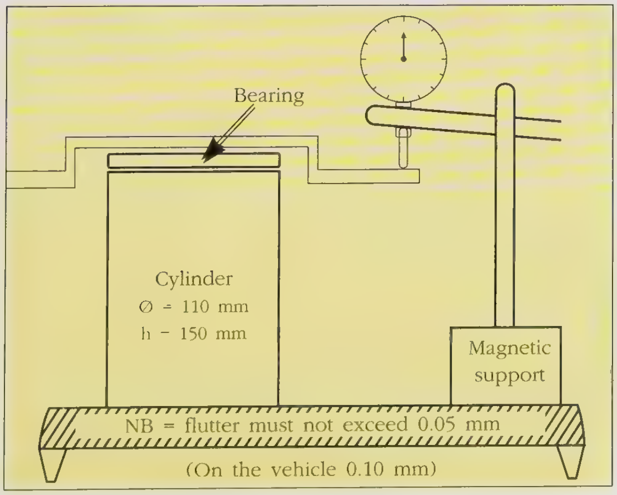
4.5 CHANGES IN DISC SIZE CHARACTERISTICS

When initial measurements of the fitted disc and successive observation do not give clear answers, it may be useful to analyse disc dimensions further.

Placing the disc on a bench as seen in the illustration, it is possible to measure its dimensions without these being affected by other brake components.

- After cleaning the **surface** coming into contact with the hub using sandpaper, the disc must be able to rest on the bench bearing without run out. This is done by holding the disc at the extremities of a diameter with the fingers and checking its vertical movement. If the disc is unstable this indicates distortion due to incorrect or excessive **tightening**.
- With the aid of a **DTI Gauge** mounted on a fixed base it is possible to measure the disc's **production run out**, provided that it has not been rectified by the mechanic at the time of fitting. This measurement is carried out by resting the DTI Gauge against the external or internal edge of the disc where the pads have not worn the braking surfaces. If the run out value measured is greater than 0.05 mm it means that the disc originally had a marked run out, a certain cause of vibration. If the value is less, then the acquired run out is measured by placing the point of the DTI Gauge at the centre of the braking surface: if it is beyond the tolerance this indicates incorrect installation that causes vibrations after a few thousand kilometres (cold judder due to a DTV increase).
- Lastly, when travelling, it is possible to determine if vibrations are caused by the front discs or the rear drums. Proceeding at low speed, pull lightly on the handbrake: if there are vibrations the problem concerns the rear drums (check and, if necessary, replace them).

Bench for checking discs.



Vibrations are produced by the rear drum: cracks and blue spots.

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BRAKING

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BREMBO ADVICE TO USERS

1 - Braking style - just like driving style - must always be adapted to climatic conditions and the state of road and traffic.

2 - Braking distance not only depends on braking system efficiency but also on the conditions of tyres and suspension.

3 - Optimal braking within a limited distance is which provides maximum deceleration without locking the wheels, the consequences of which would be the loss of vehicle stability and an increase in braking distance.

4 - In the case of long downhill stretches it is advisable to use the engine brake and above all not to switch off the engine. After a brief stop, check pedal efficiency before starting off again.

5 - When the situation requires a prolonged and continuous use of the braking system, release pressure on the brake pedal from time to time for a brief period.

6 - After stopping for a long period the first braking actions will be affected by the stop, and also by climatic conditions. A certain number of braking actions should be performed in order to re-establish the full efficiency of the disc-pad unit.

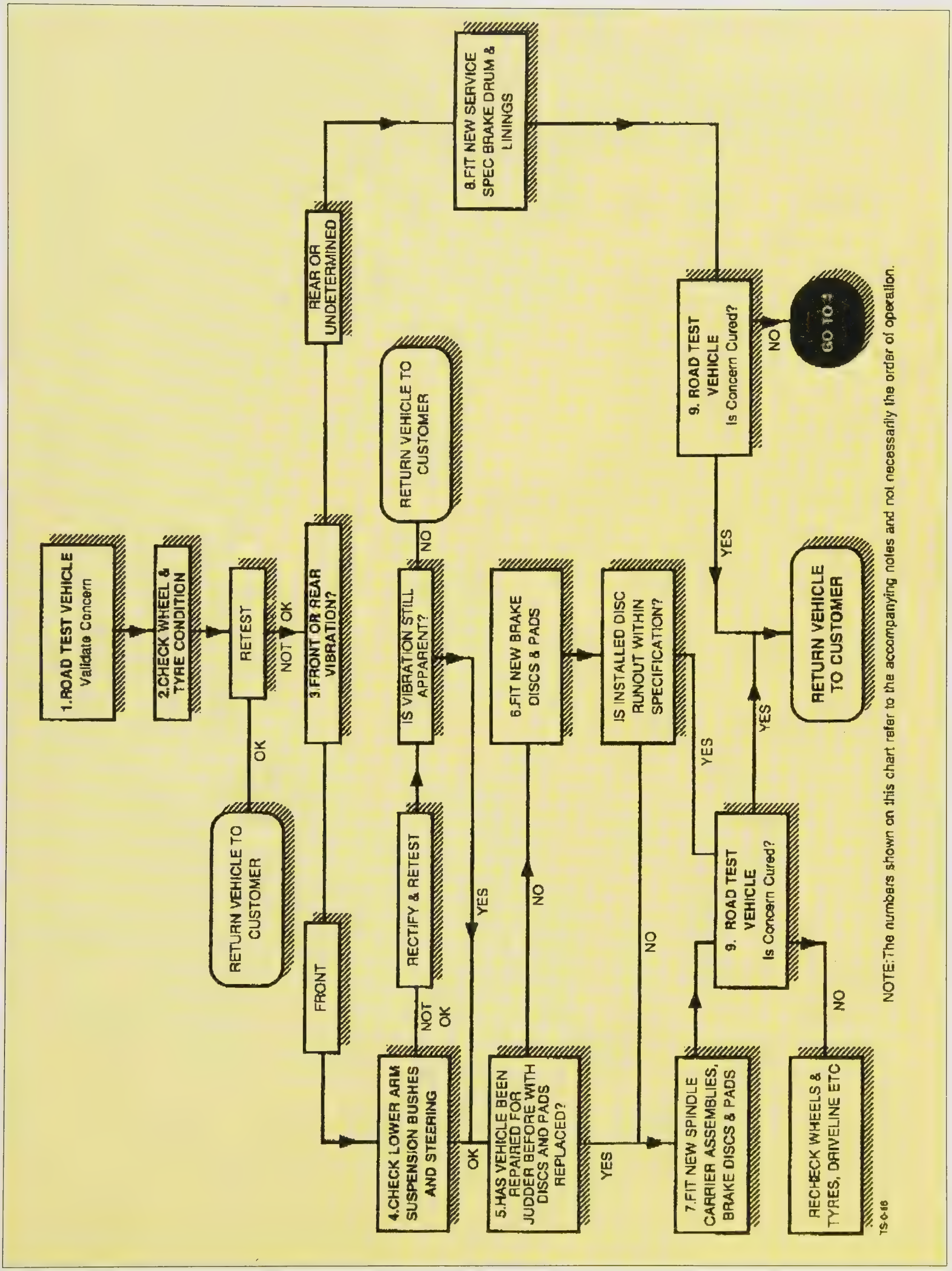
7 - Ensure that all parts of the braking system function correctly: fluid level, pad and disc wear, rear brake lights, parking brake indicator, etc. Follow the manufacturers instructions as regards replacement of the brake fluid (frequency, quality).

8 - Periodically check the efficiency of the parking brake by trying to move the vehicle when this brake is on.

9 - Only use spare parts produced by recognised manufacturers.

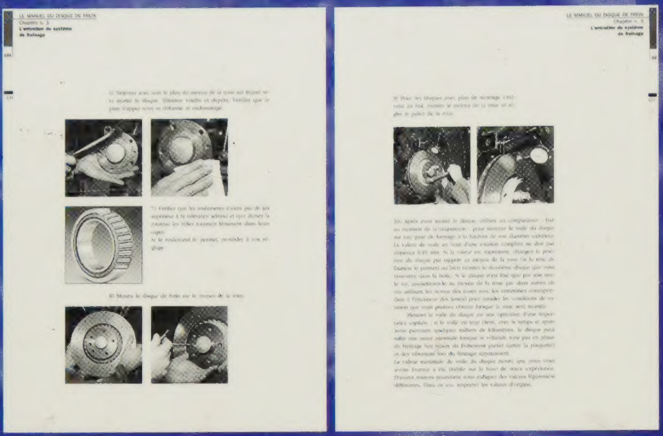
10 - If possible, use a vehicle equipped with a braking control system (ABS, etc.).

Reproduction of a flowchart produced by a manufacturer for the diagnosis of vibrations on a "critical" vehicle. A document intended for the dealer network.

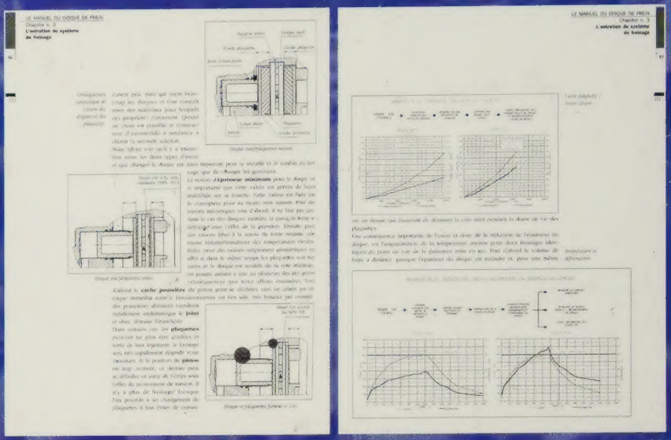


2.1

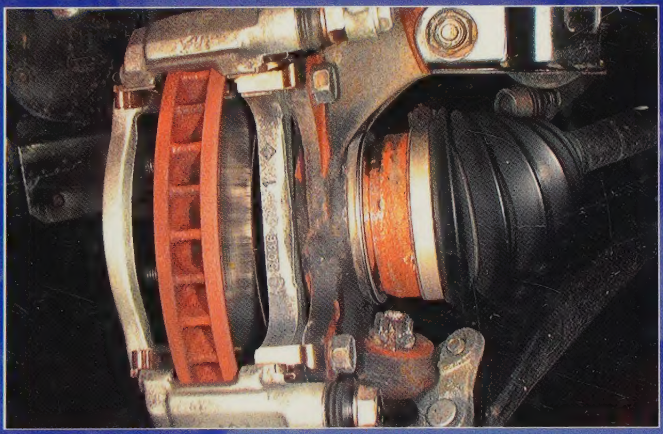
AUTOMOTIVE **DISC BRAKE** MANUAL



Clearly captioned step-by-step pictures show precisely how to perform many tasks



The clearly presented text is fully illustrated with photographs and diagrams



Inside this Manual:

- **Overview of disc brake systems**
- **Theory and practice of operation**
- **Design, manufacture and testing**
- **Maintenance requirements**
- **Causes and suppression of brake noise**
- **Symptoms and causes of abnormal wear**
- **Why and when to renew components**
- **Of interest to NVQ students**

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ISBN 1 85960 54

H956276